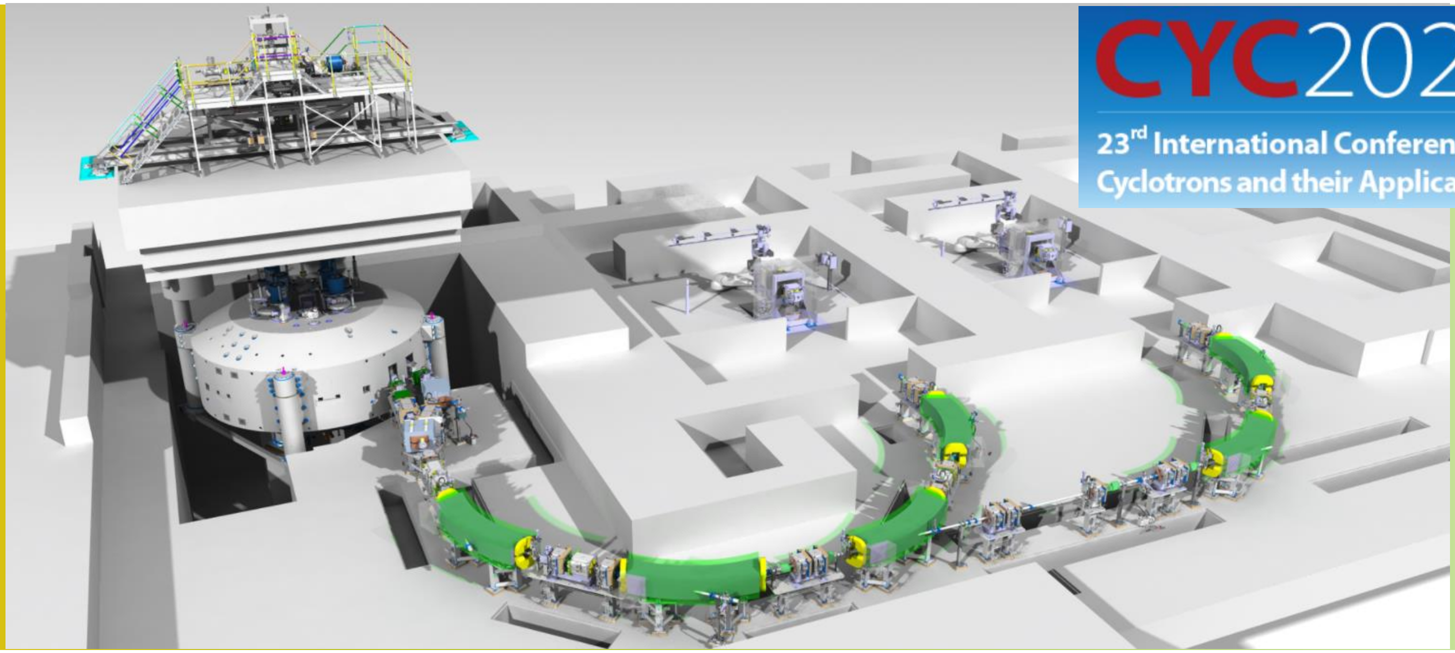


CYC2022
23rd International Conference on Cyclotrons and their Applications
Dec. 5 - 9, 2022 • Beijing, China

Status on NHa C400 Cyclotron for Hadrontherapy

O. Cosson[1], P. Velten[1], L. Koffel[2], S. Deprez[2], Y. Otu[2], G. Goose[2], P. Cailliau[2], W. Kleeven[2], J. Mandrillon[2] (speaker) , V Nuttens[2] , M. Abs[2] , Y. Paradis[2] , X. Donzel[2] , L. Maunoury[1]

[1] NHa ; [2] IBA

NHa NORMANDY HADRONTHERAPY

Certified B Corporation Life, Science. iba

Introducing …

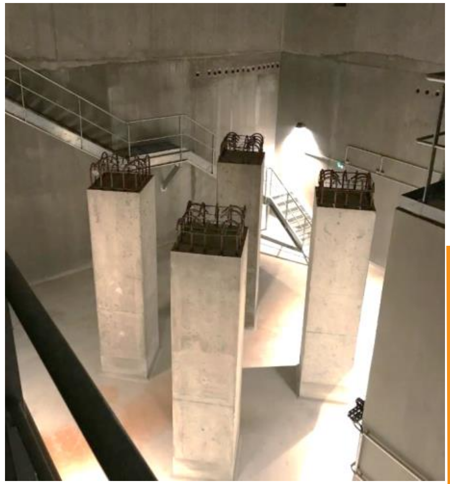
NHa is a company located in Caen, France

NHa 2 main shareholders are & *(public private company with **Normandy Region** as main shareholder)*

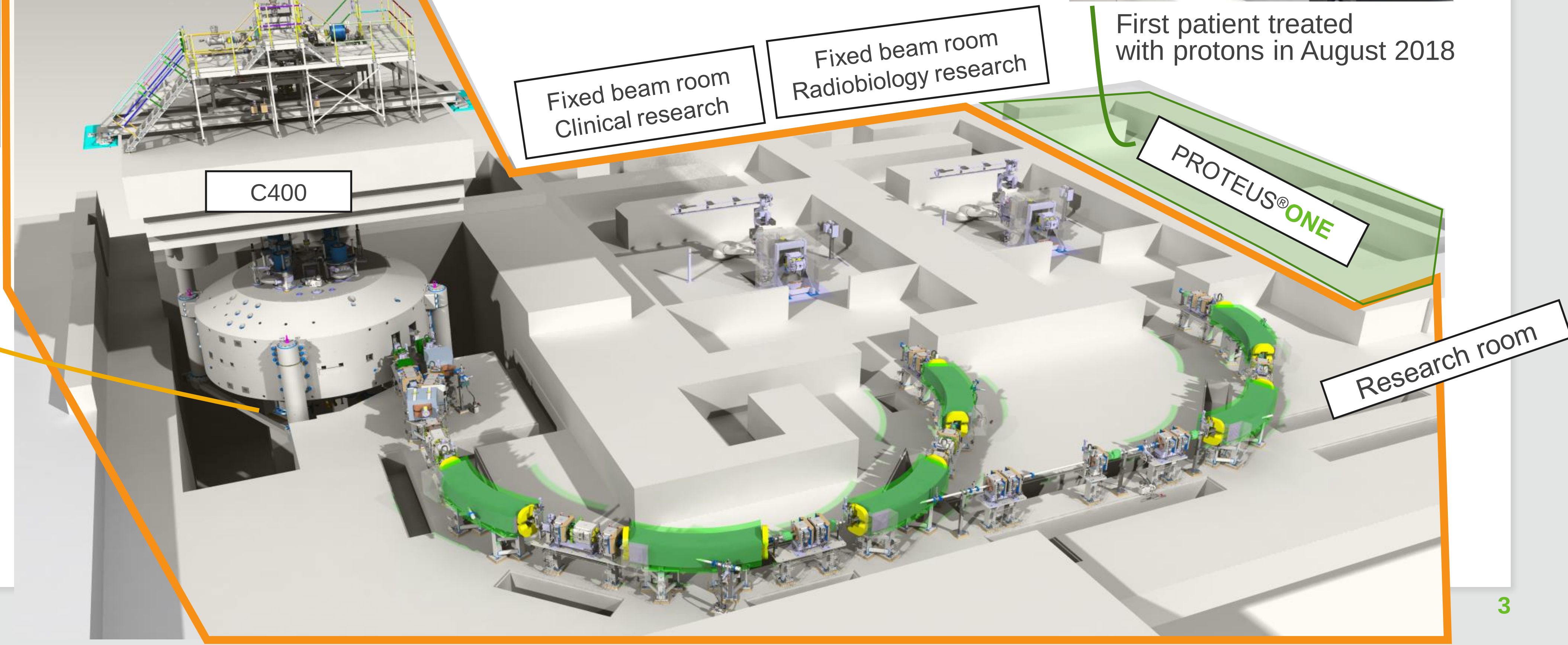
Design, produce and market the ion therapy system

involve in the design

First site is CYCLHAD project

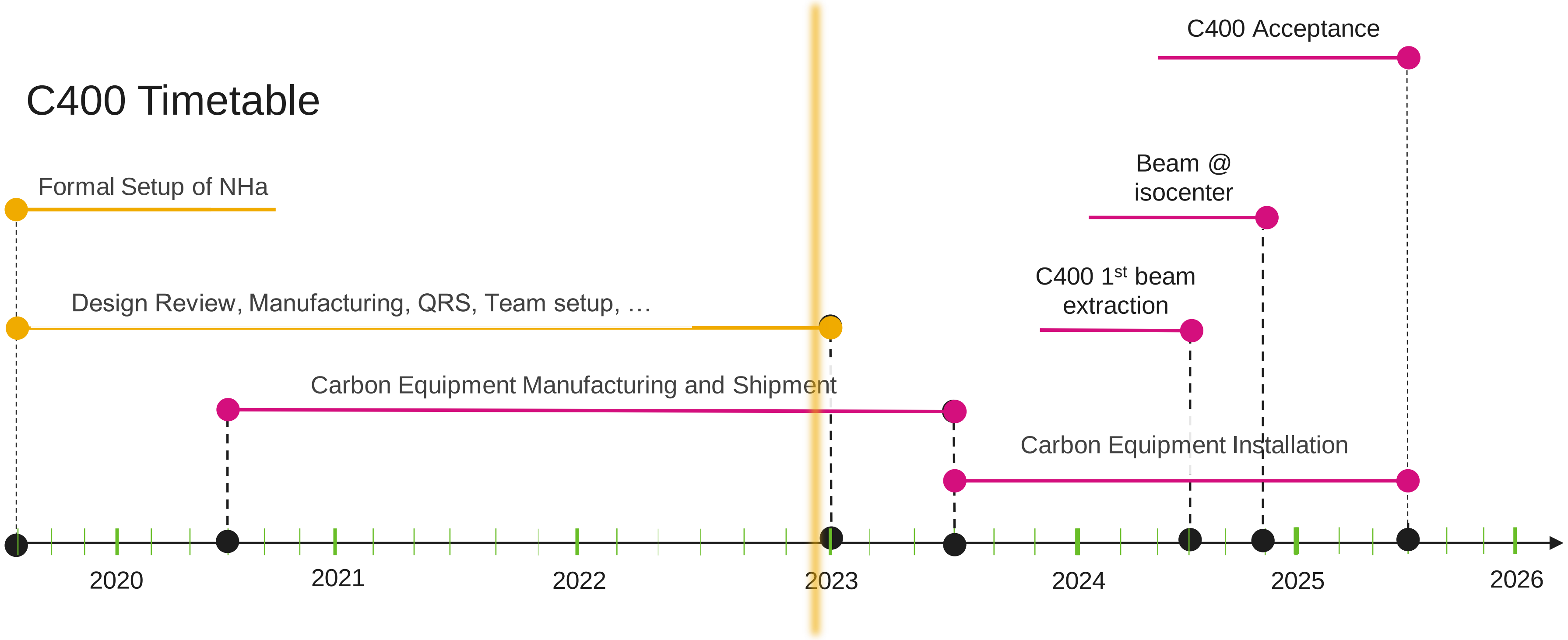


Bunker ready to host the C400



First patient treated
with protons in August 2018

C400 timetable



Design overview

Present work is based on the design from the IBA-JINR collaboration, reviewed by experts of our community.

Table B1: Summary of the C400 cyclotron Main parameters

General properties		
accelerated particles	=	H_2^+, $^4He^{2+}$, $(^6Li^{3+})$, $(^{10}B^{5+})$, $^{12}C^{6+}$
Injection energy	26 kV ⇐	25 keV/Z
final energy of ions, protons	260<<270 ≈	400 MeV/amu 265 MeV/amu
extraction efficiency		70 % (by deflector)
number of turns	~2100 ⇐	~1700
Magnetic system		
total weight	736.8 Tons ⇐	700 tons
outer diameter	7m ⇐	6.6 m
height	=	3.4 m
pole radius	=	1.87 m
valley depth	=	60 cm
bending limit	=	K = 1600
hill field	≈	4.5 T
valley field	≈	2.45 T
RF system		
radial dimension	≈	187 cm
vertical dimension	≈	116 cm
frequency	=	75 MHz
operation	=	4th harmonic
number of dees	=	2
dee voltage center extraction	~60 kV ⇐ ~150 kV ⇐	 80 kV 170 kV

We didn't change C400 parameters from 2009

… but we did an extra pass on all subsystems.

Design Report of Superconducting Cyclotron C400 for Hadron Treatment

JINR
V. Aleksandrov, G. Shirkov, E. Syresin,
G. Karamysheva, N. Kazarinov, S. Kostromin, N. Morozov, E. Samsonov, V. Shevtsov, A. Tusikov, V.Romanov

IBA
Y. Jongen,
W. Kleeven, S. Zaremba, D.Vandeplassche, F. Stichelbaut,
S. Deneuter, S Dépréz, W. Beeckman

SIGMAPHI & co
J-L. Lancelot,
W. Beeckman, F. Forest, M.N. Wilson, C. Monroe

International Experts Design Review
Louvain-la-Neuve
22 & 23 April 2009

JOINT INSTITUTE FOR NUCLEAR RESEARCH

ΣΦ SIGMAPHI

C400 Design review April 2009 IBA Confidential

Design overview

Basics:

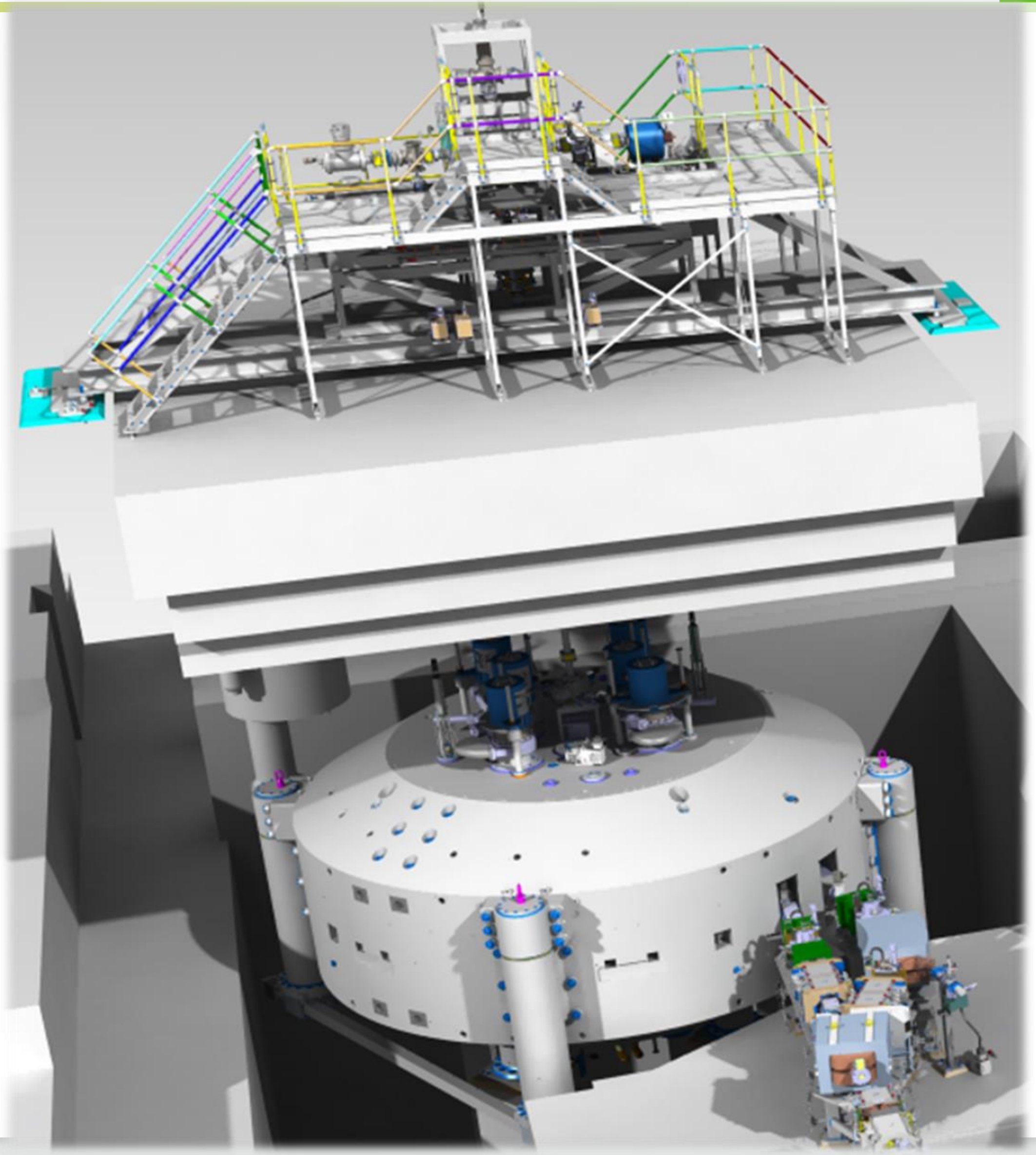
- 3 sources H_2^{+}, $^4He^{2+}$ & $^{12}C^{6+}$

- Dual extraction:
  - **H_2^{+} @ ~265 MeV/u**: protons extracted via stripping
  - **$^4He^{2+}$ & $^{12}C^{6+}$ @ 400 MeV/u**: via electrostatic deflector

- RF: 75MHz for $^{12}C^{6+}$, 75.6MHz for H_2^{+}, Harmonic #4

- Large "compact" magnet
  - 740 Tons – 7m diameter yoke - pole radius 1.87m
  - **pole** is **4-fold symmetry / Elliptical gap / Spiralized poles**

- Cryogenic coils
  - max field 4.5T,
  - **2 sub-coils/coil** to adapt field to particle masses discrepancies.



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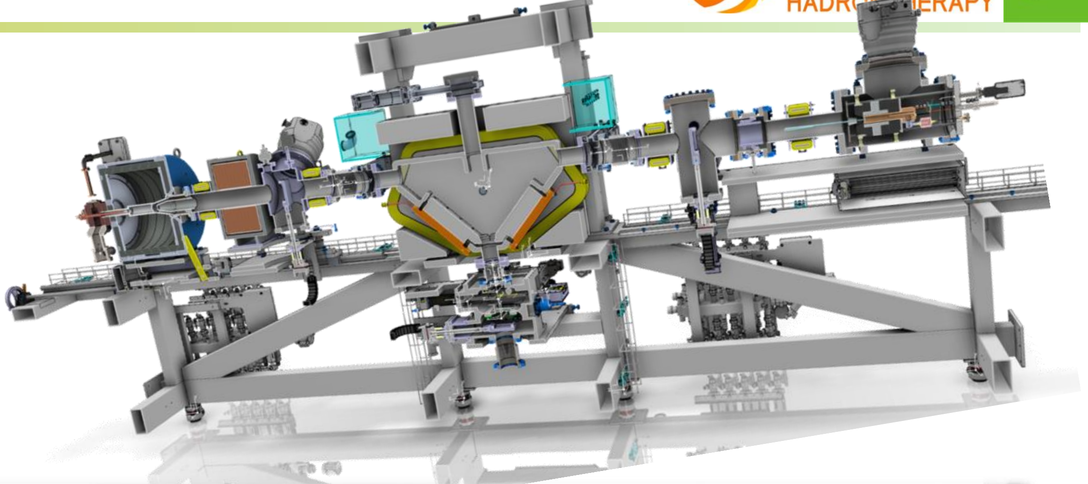
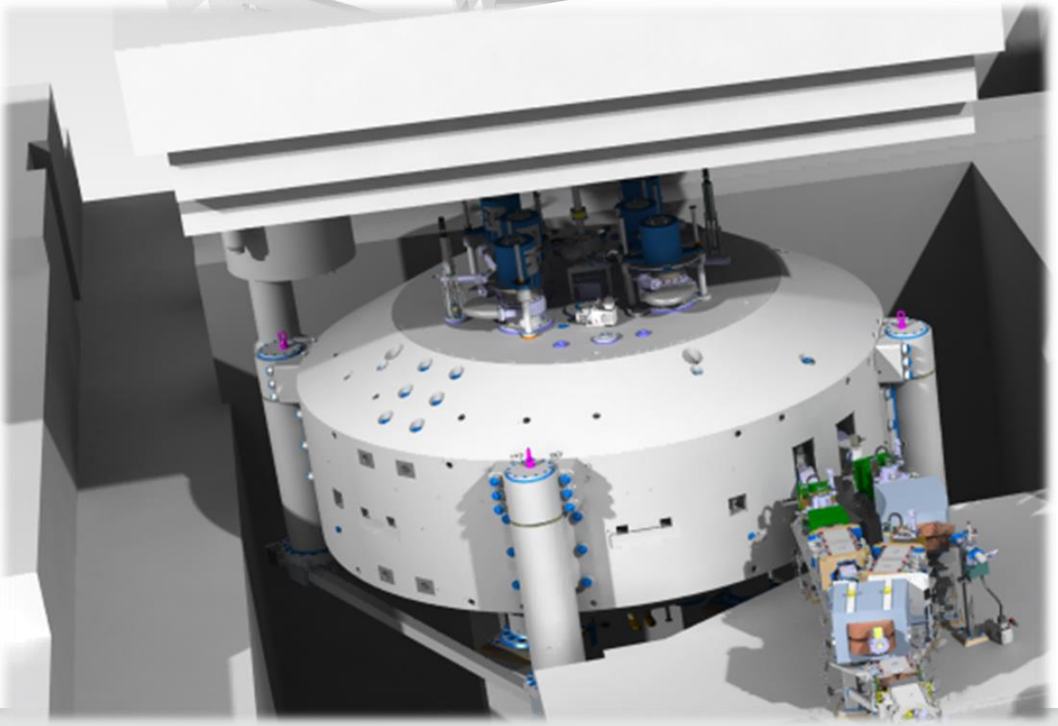


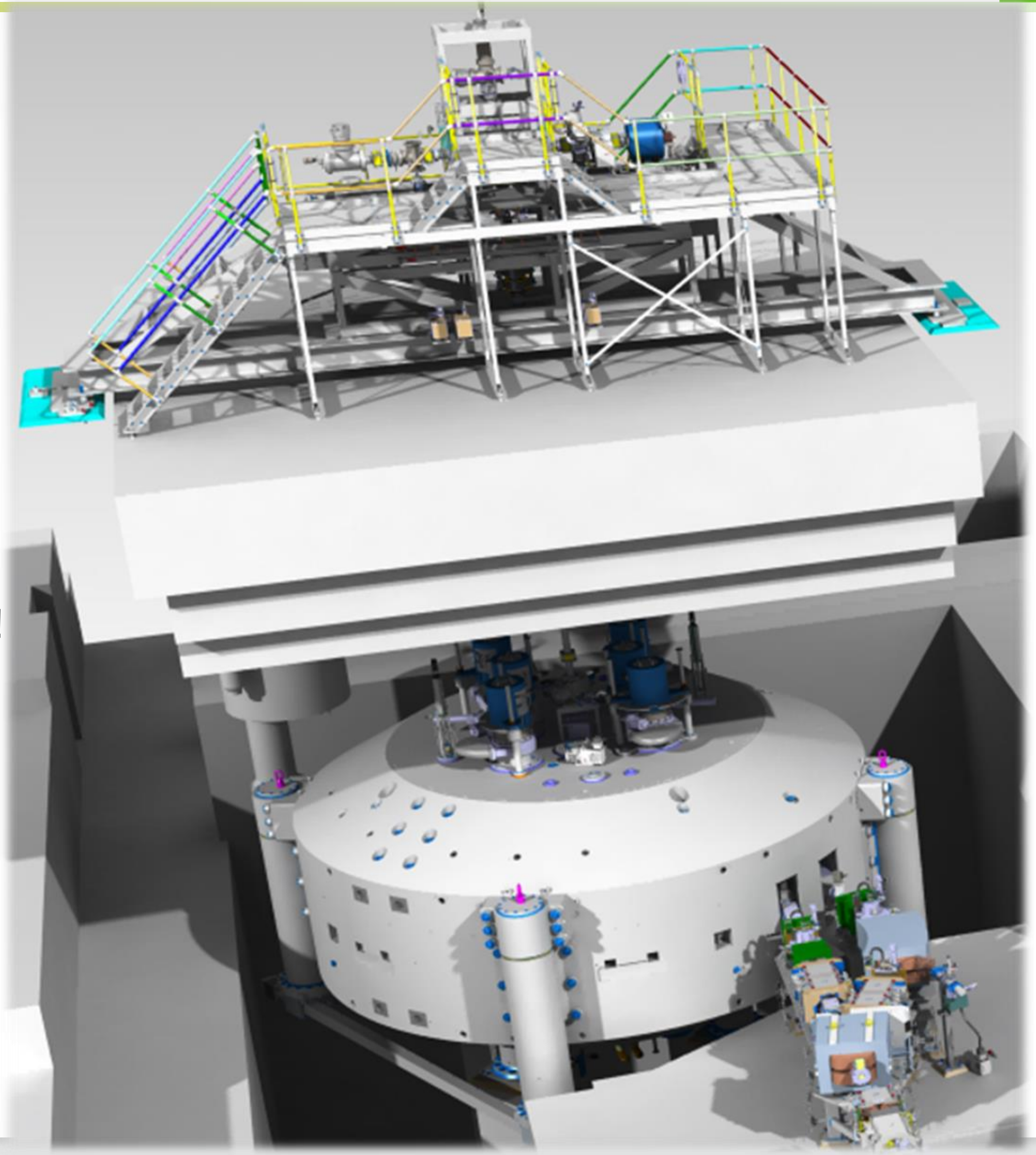


Design overview

Inherent challenges

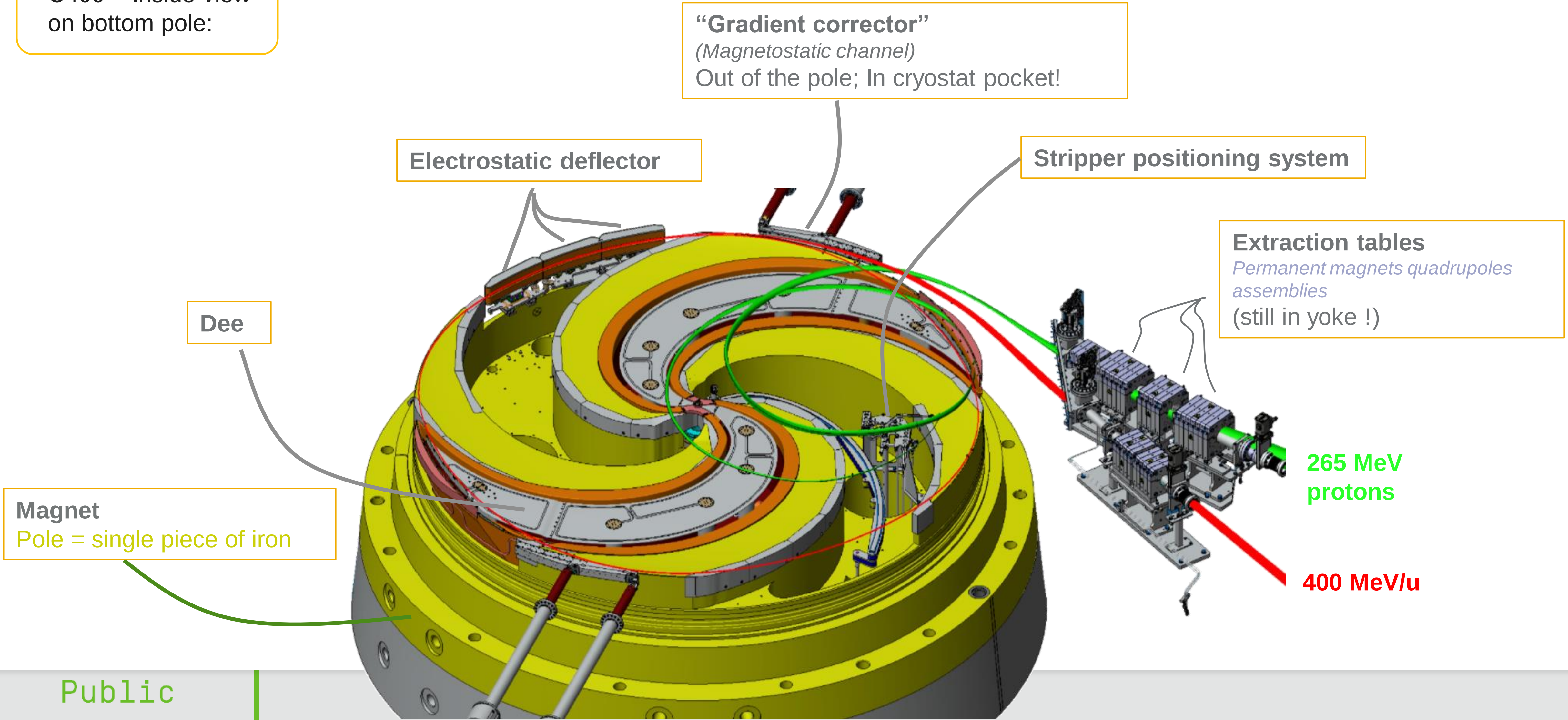
- Big cyclotron related:
  - Size & precision
  - Handling / transport / on site assembly / maintenance
  - Managing Beam Tuning capabilities
- Vacuum requirements @ 2 10^{-7} mbar
- Fundamental resonance crossing 3Vr=4

See poster !



In this talk:

C400 – Inside view on bottom pole:



Magnet updates

1

Diameter of the pumping holes increased (300 to 440 /520mm dia.), *with small impact on hills azimuthal width.*

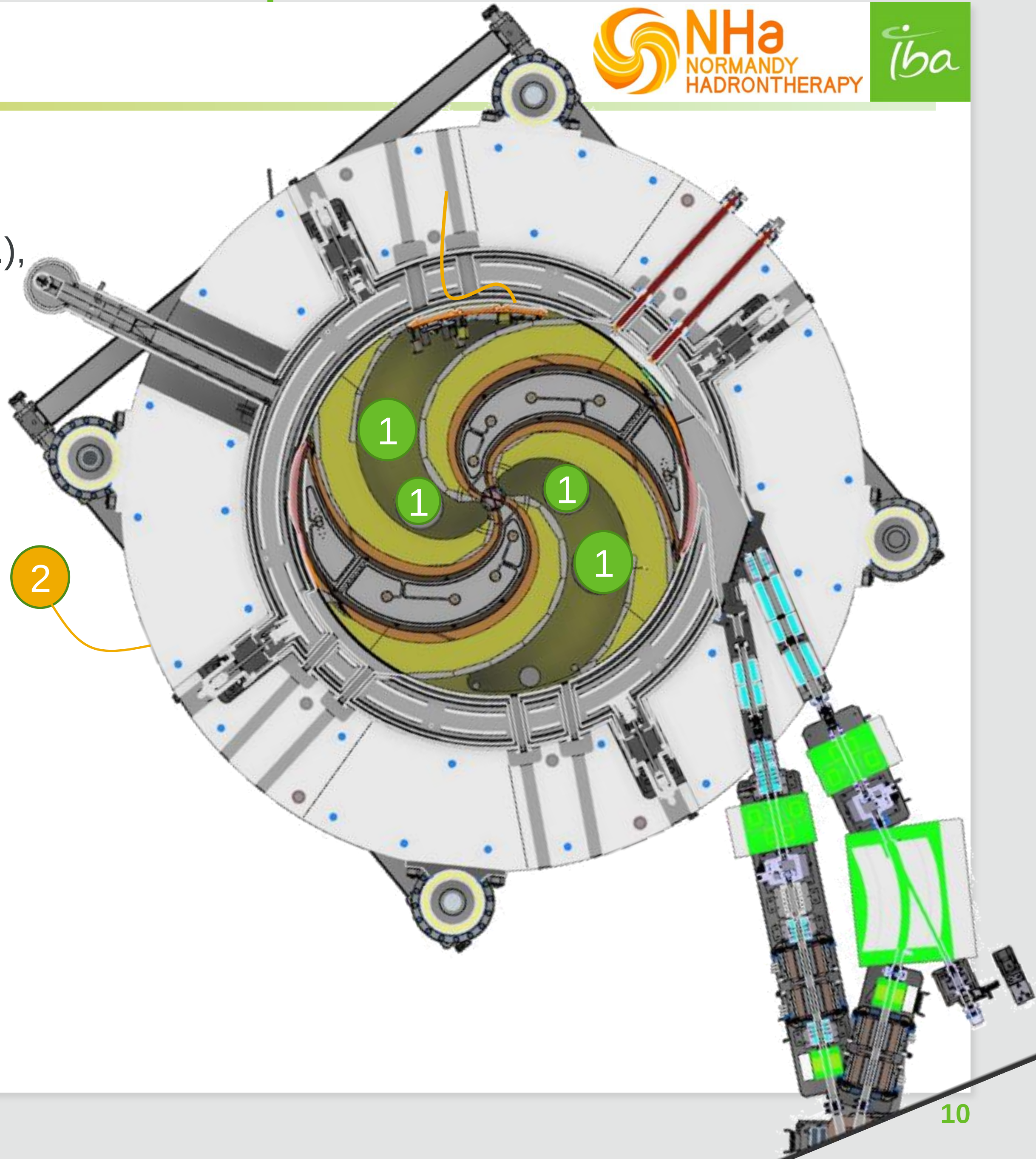
Vacuum requirements, reducing pumping time

2

Increase of Yoke radius because of all the modifications

Requirements on hoop stress for selected SC conductor

(more iron meaning less current & less stress)



Magnet updates

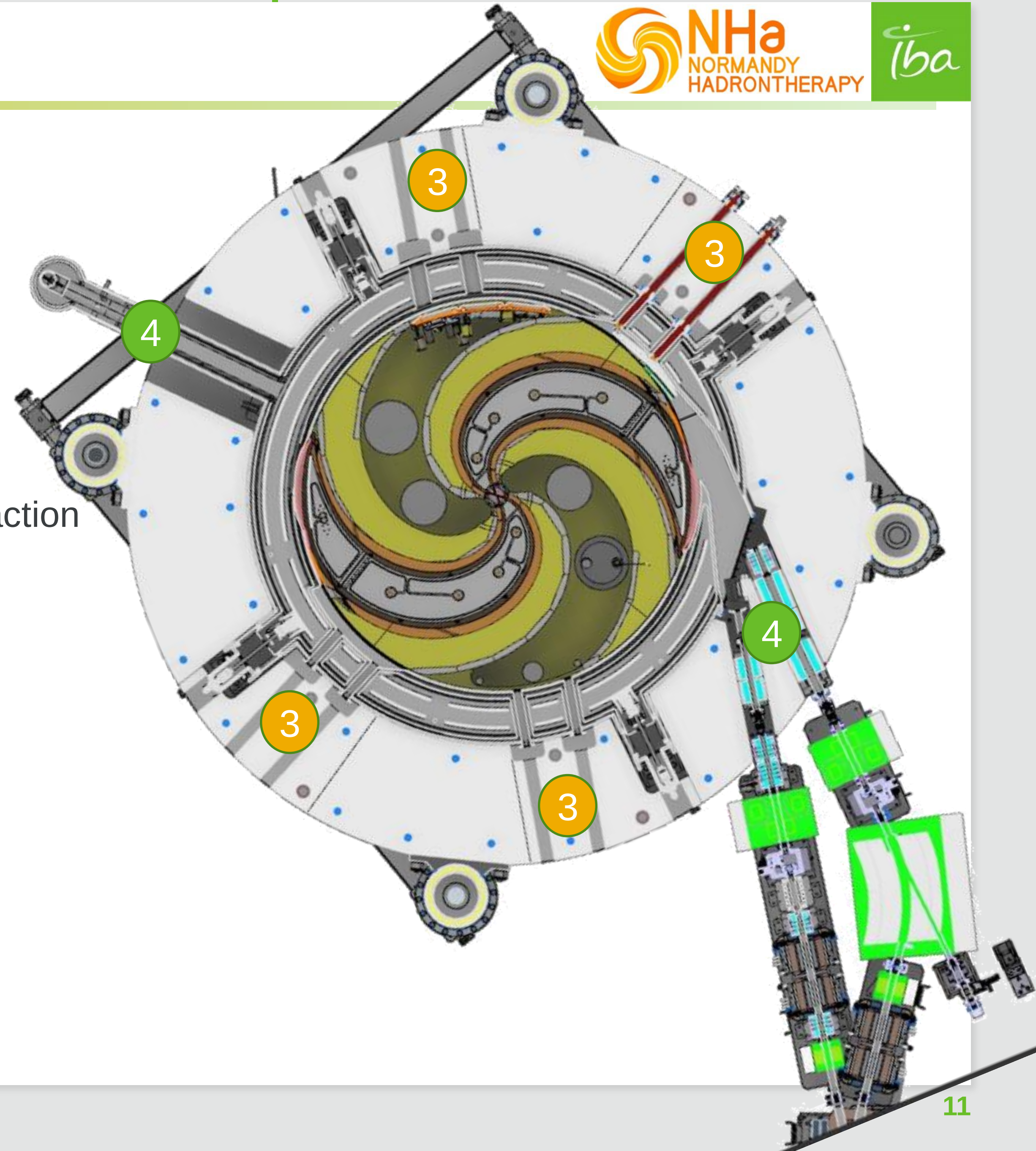
3

Yoke **penetrations** redefined + relocated + made in 180° symmetry

4

Service turret for SC coils* moved to an angle opposite to the extraction

Imposed by cryogenic design

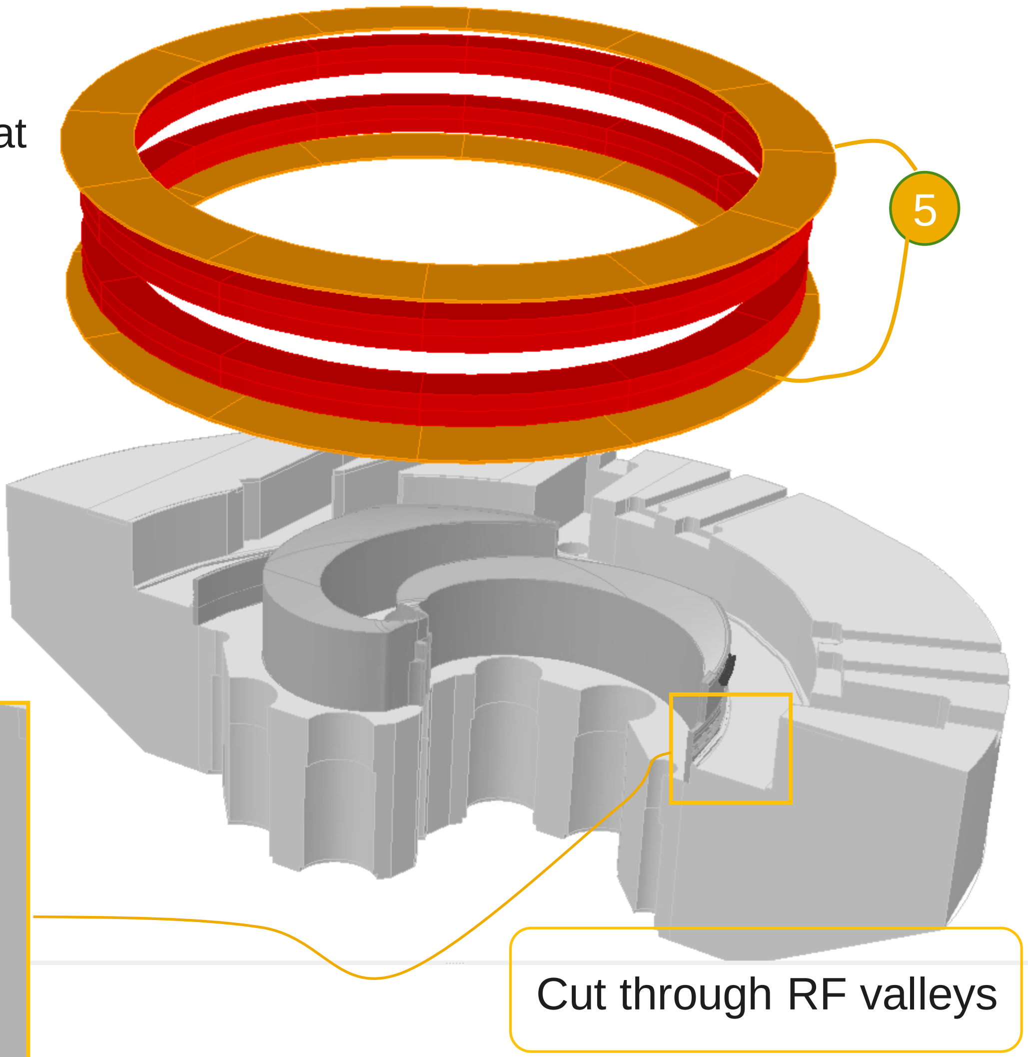


** 2009 Venting touret has been removed*

Magnet updates

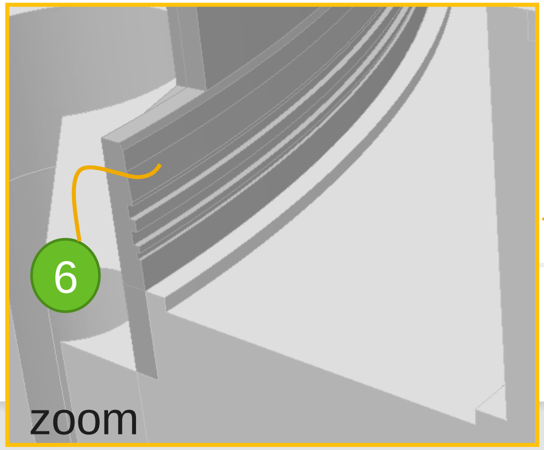
Median plan correction 5

Resistive compensation coils on top & bottom of the cryostat



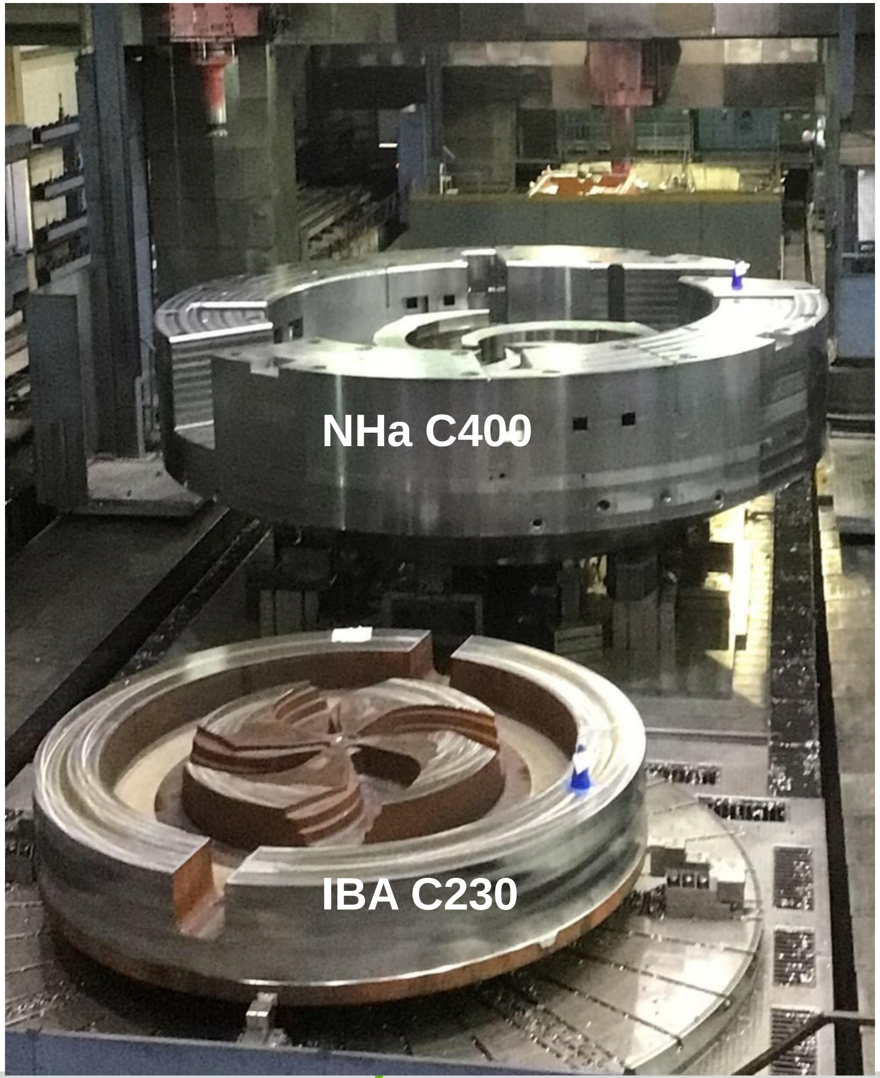
Radial vacuum seals between pole & cryostat

Iron ring in the bottom of the valley, 6



Magnet

Manufacturing



Magnet

Manufacturing

Magnet

Coils & cryostat

Manufacturing

Coils

Ramping time : 2 hours

Time to switch between particles : < 15 min

Stored energy: ~55.6 MJ

Cold mass at 4.3K: 14.6 tons

turns per coil : 1344

Supra material : NbTi

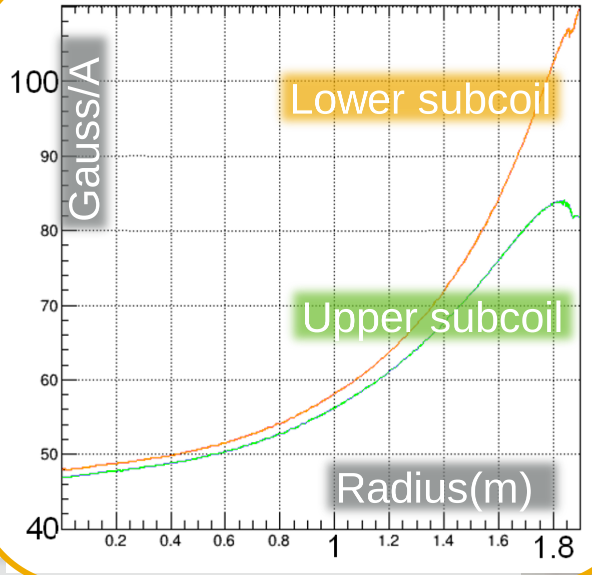
Critical current: 2800 A @ 4,5 T @ 4,2 K

Conductor peak field: 3.9T

Current density : ~31 A/mm²

Coils current:

- PS1 ~1034 A (on all 4 sub coils)
- PS2 (max 120A) (only on 2 sub coils)



Cryostat

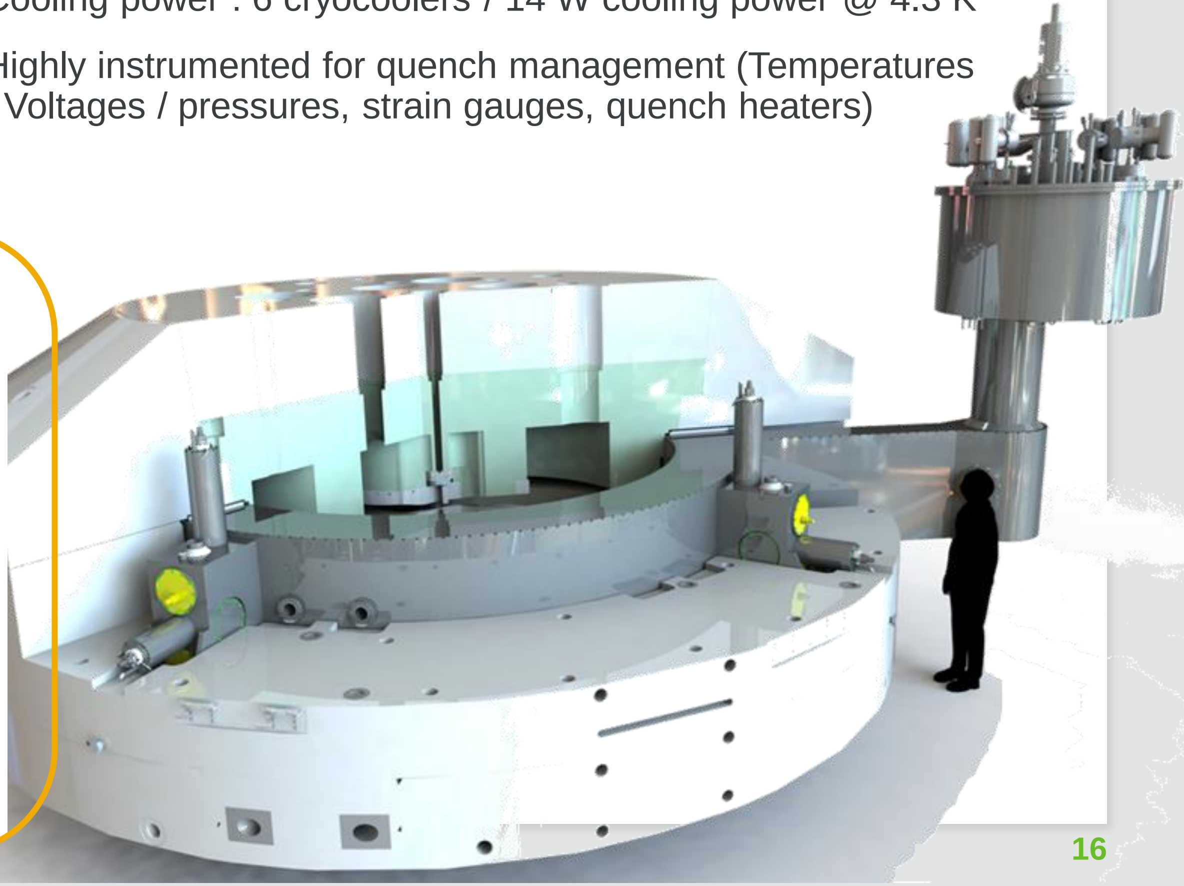
Outer diameter: 4.8m

Liquid helium bath T°: 4.3 K

Liquid helium thermosyphon circulation system

Cooling power : 6 cryocoolers / 14 W cooling power @ 4.3 K

Highly instrumented for quench management (Temperatures / Voltages / pressures, strain gauges, quench heaters)



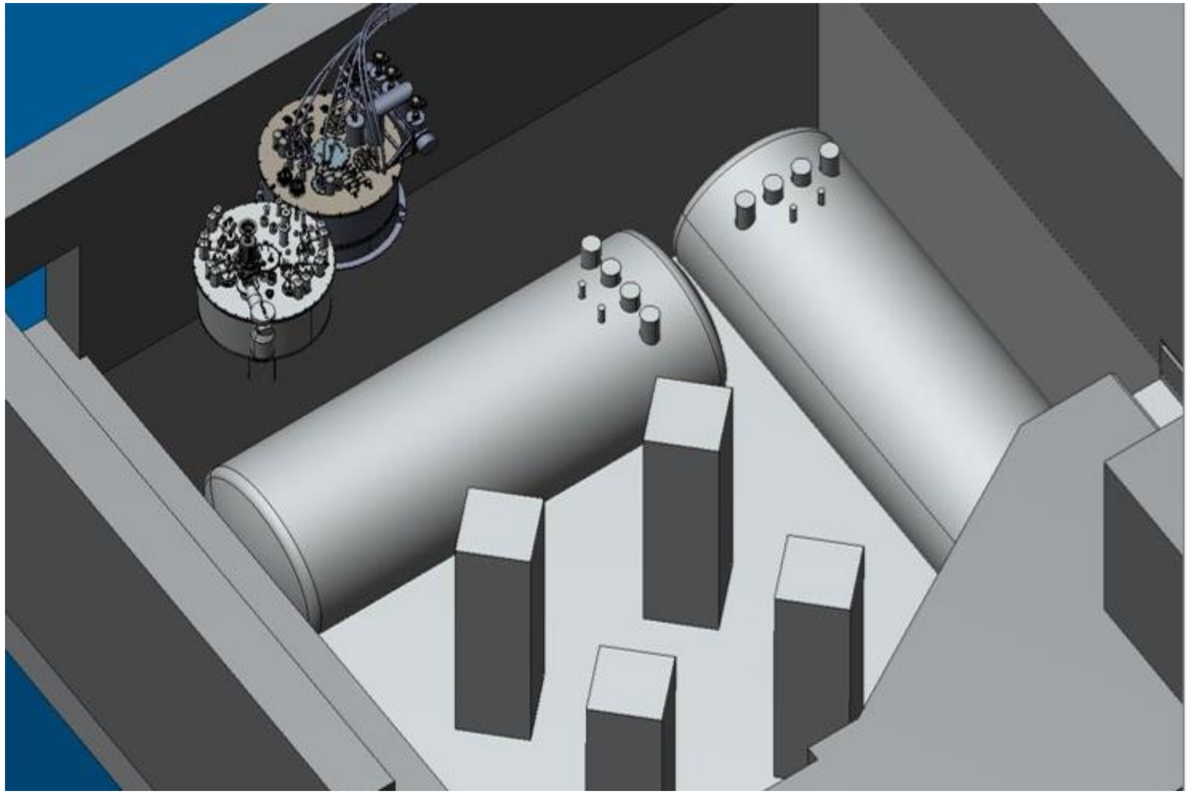
Coils & cryostat

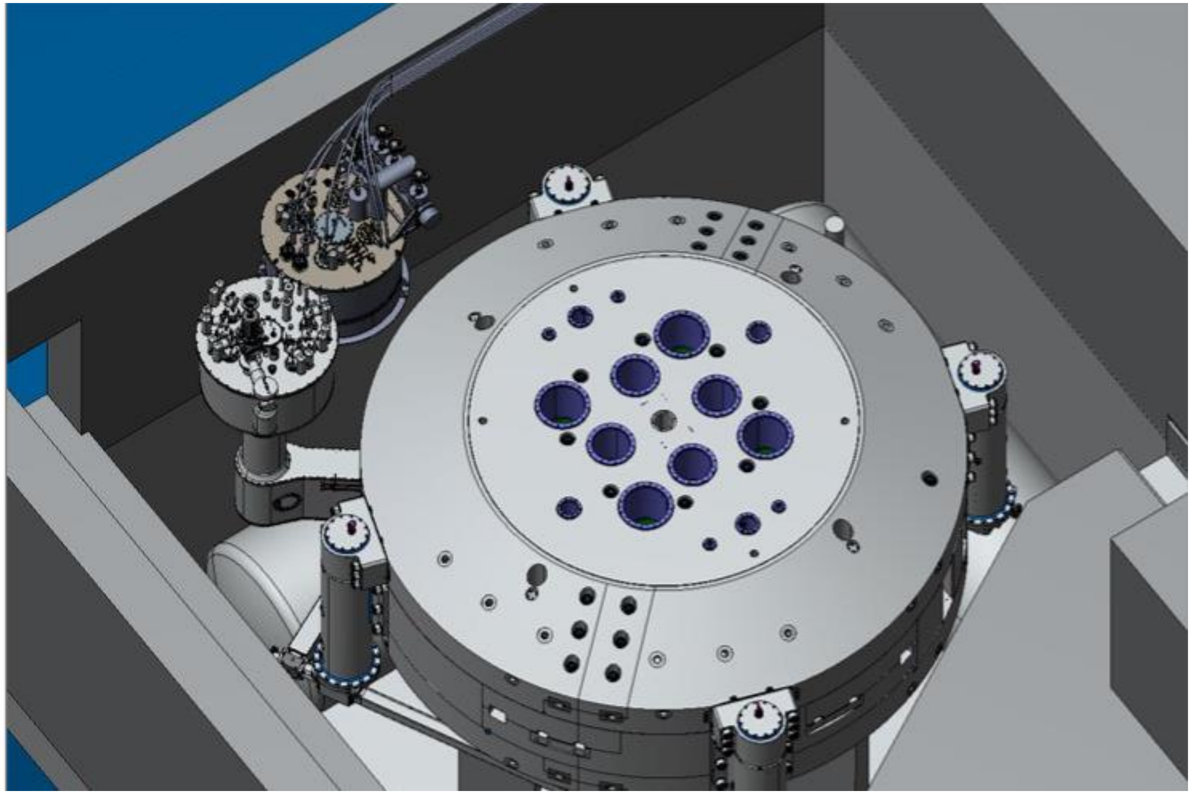
Under study

Liquefaction

Since 2009, price of Helium has been multiplied by > 6

Tanks installed below c400 to recover vaporized Helium during potential quenches.





Coils & cryostat

Manufacturing

NHa NORMANDY HADRONTHERAPY

iba

Helium vessel (Coils inside, welding completed)

SIGMAPHI ACCELERATOR TECHNOLOGIES

Mapping wheel

Drawings released

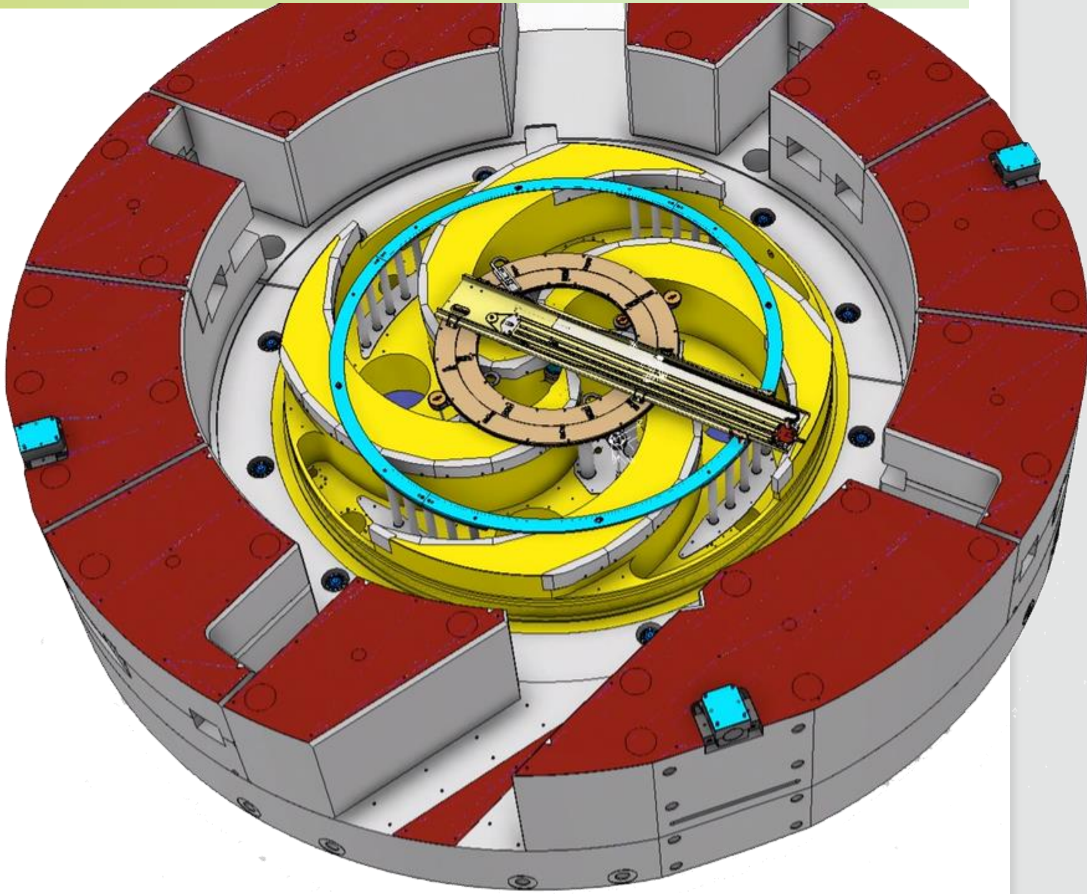
NHa NORMANDY HADRONTHERAPY

iba

Mapping

On critical path once cryostat in place

Mapping phase: 88 (!) pole edges to machine iteratively



Requirements for the wheel:

Down to (0.25° & 2mm steps) resolution needed

➔ fast mapping option with search coil

2000 turns | harmonic #4

➔ high accuracy (position / field)

- with mechanics *(clearance management, rigidity …)*
- Possibility to map under vacuum
- Hall probe

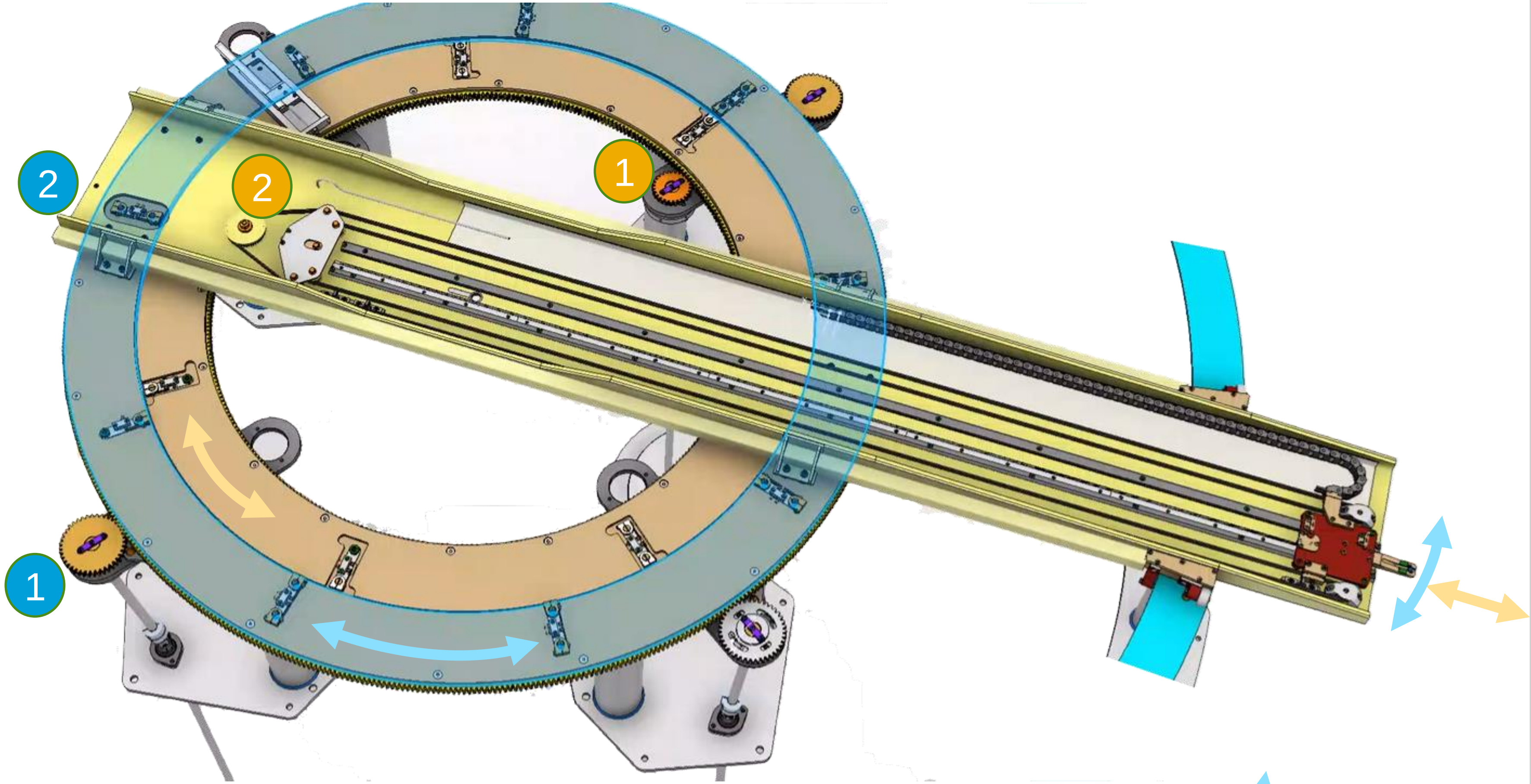
Use of polymers & composites

Non-magnetic / No induction / No thermal dilatation

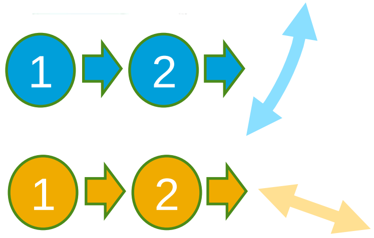
Mapping wheel

Drawings released

Motions



Independent rotation and translation of the shuttle, driven through pumping holes, via 2 independent discs.

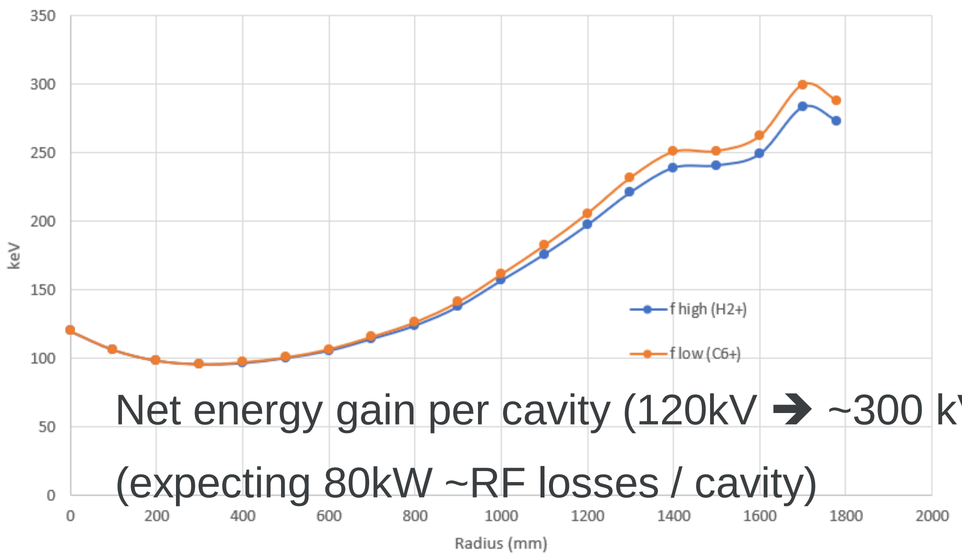


Power consumption has been optimized

mainly working on Dee stems geometry & acceleration gaps width adjustments.

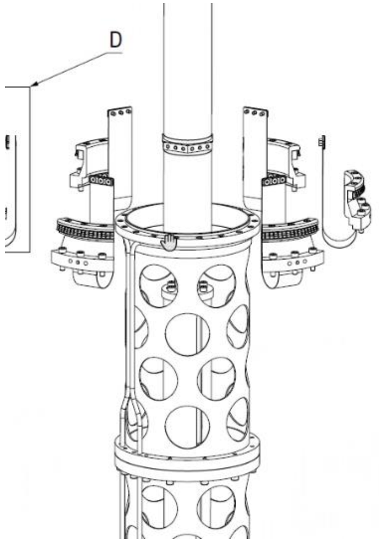
Cyclotron equipped with 4 tuners

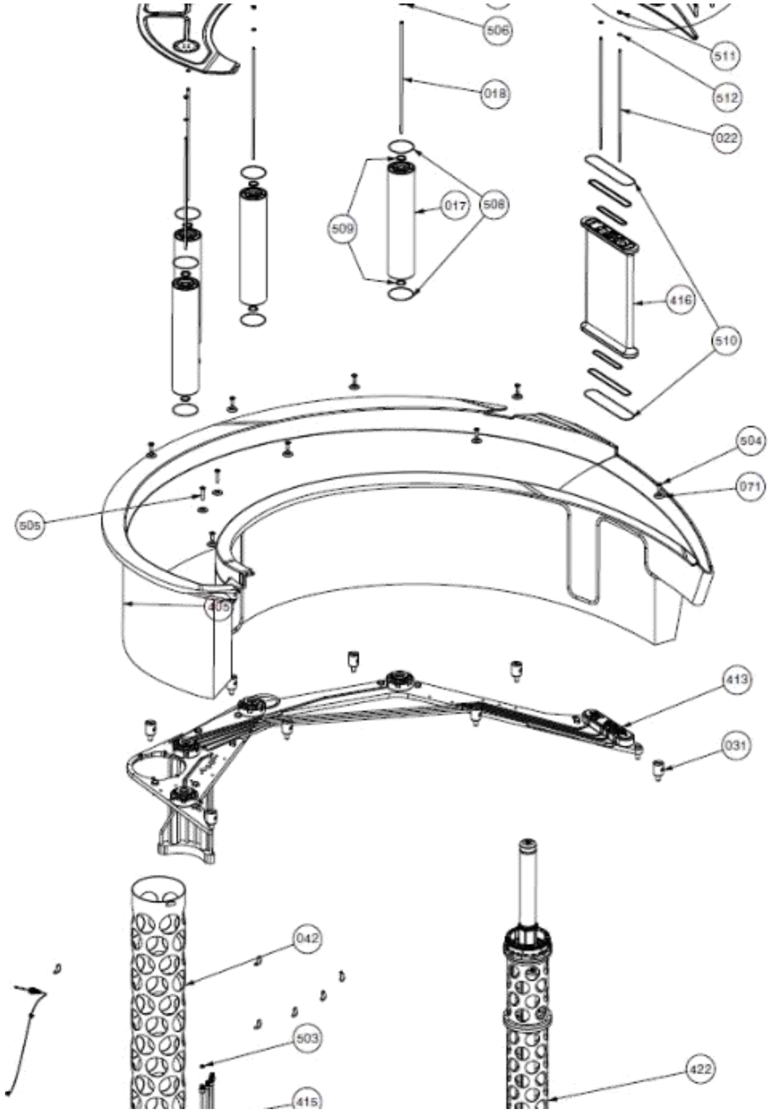
for 1 MHz max frequency tunning – 200mm span.



Net energy gain per cavity (120kV ➔ ~300 kV)

(expecting 80kW ~RF losses / cavity)

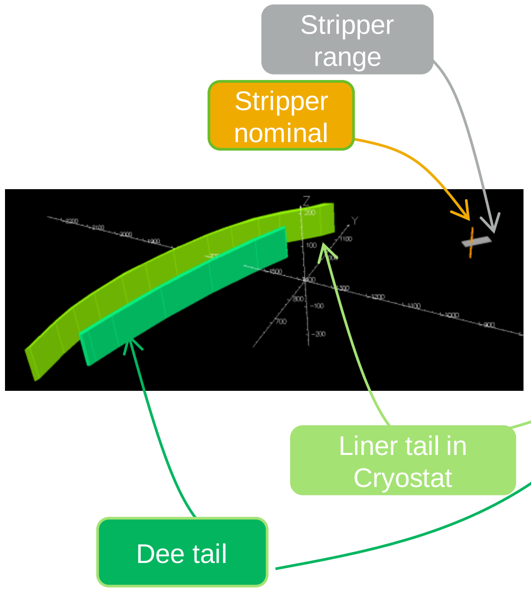


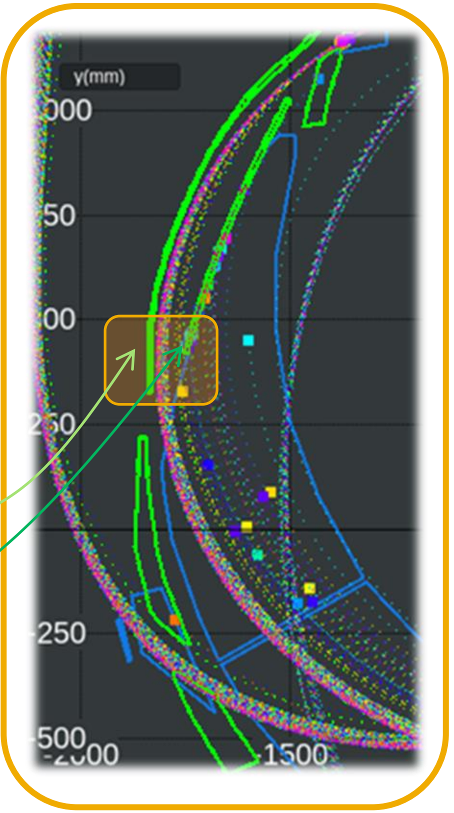


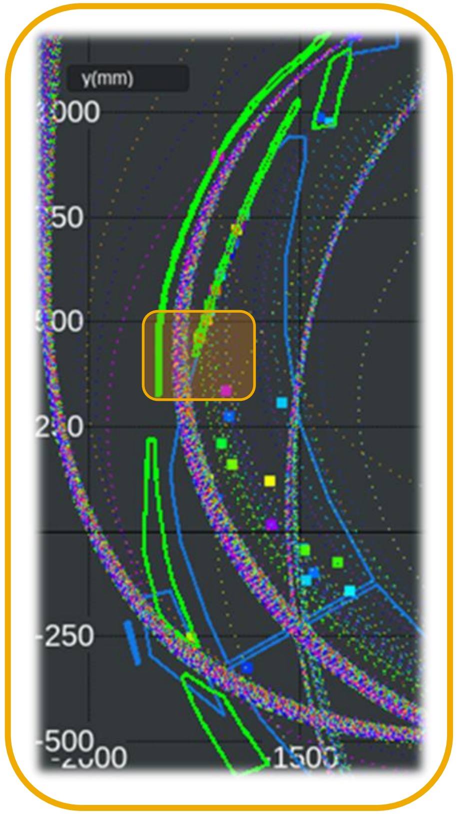
Each cavity powered by 128kW solid state amplifier (IBA design).

Manufacturing

proton loop management



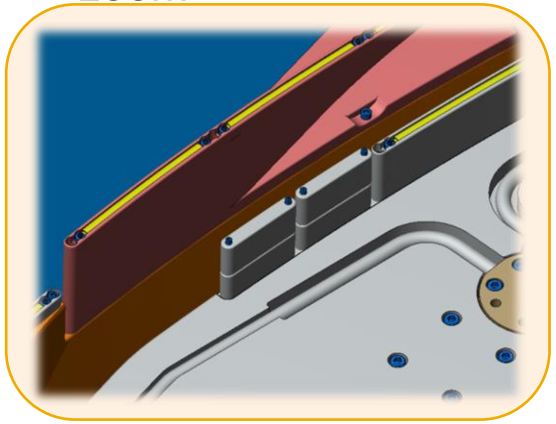




Proton beam between dee tail & RF Liner extension in cryostat

2 cases: 2 possible locations of stripper foil

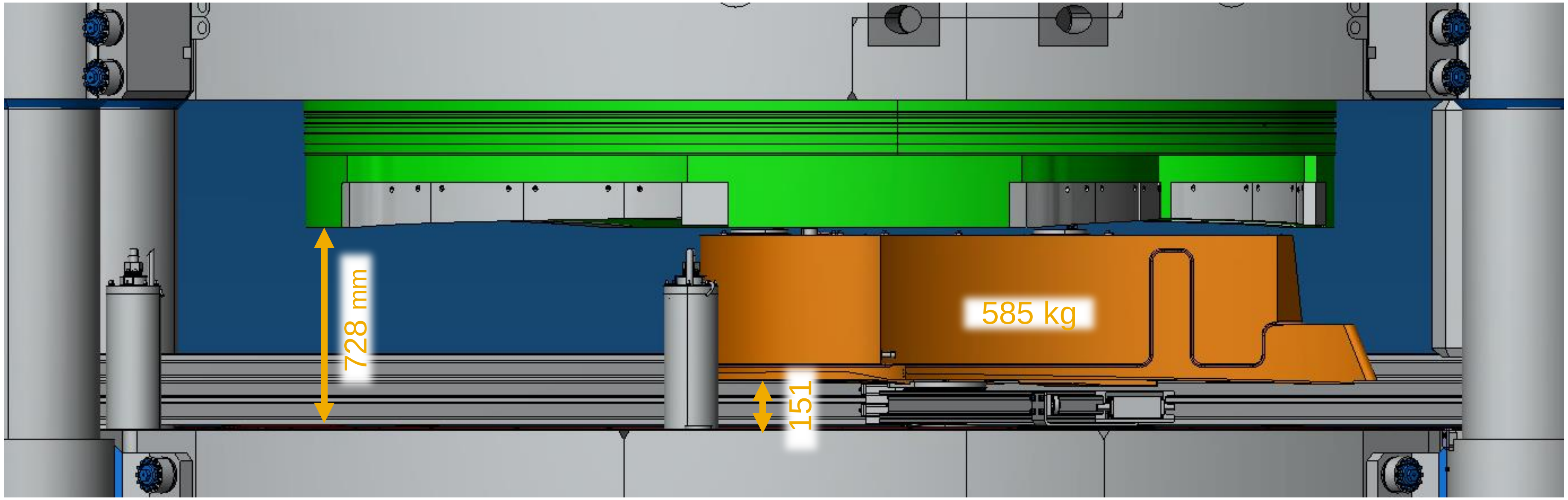
zoom



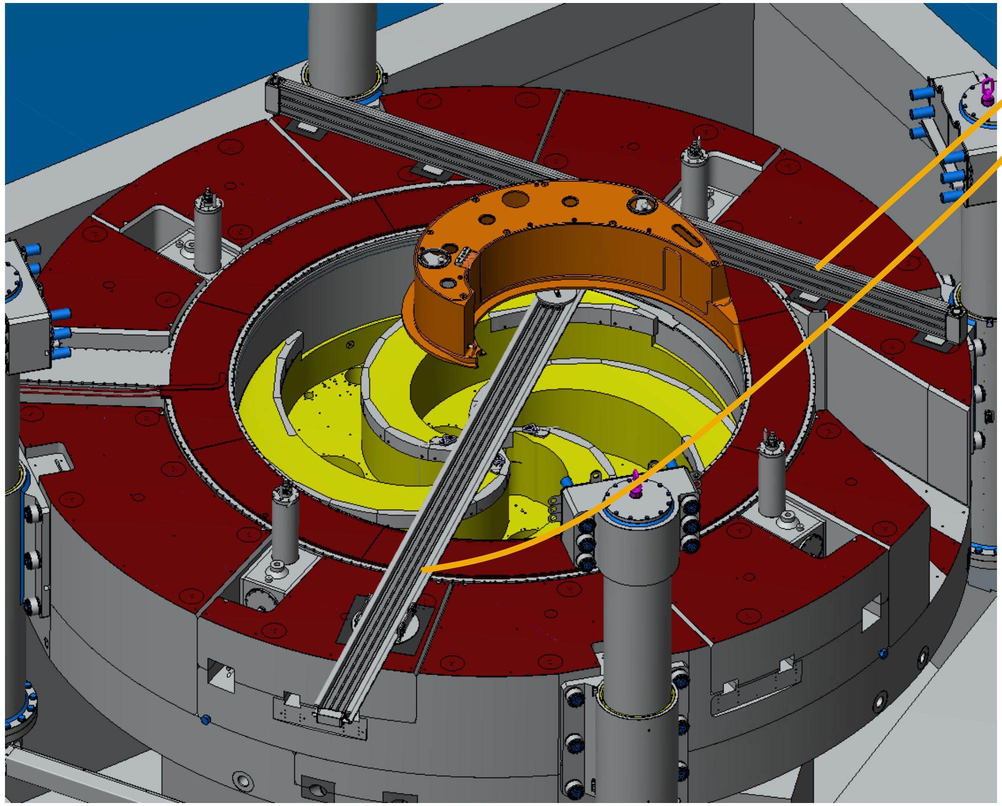
Additional tails once proton extraction tuned*.

** to enhance carbons energy gain per turn*

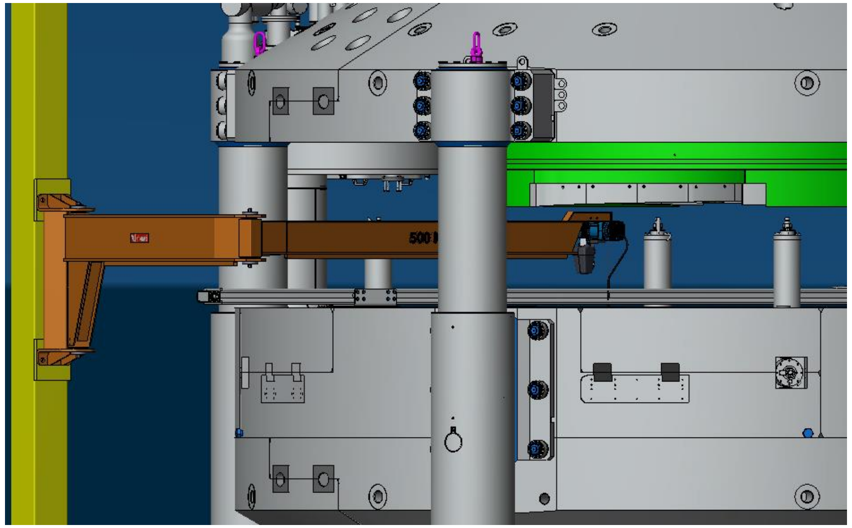
Cavity insertion



Cavity insertion



Rails with trolleys to position the cavity in the horizontal plane before lifting it through the pumping holes.



A 500 kg jib crane will help the insertion of the rails itself

RF

Manufacturing

Process: Sheet metal work (boiler), TIG welding, re-machining

Electrostatic deflector (ESD) & Magnetostatic channel (Gradient corrector – GC)

Their locations affect: Transmission / Emittances size & orientation / position at cryostat exit flange.

➔ **Actuators**

ESD

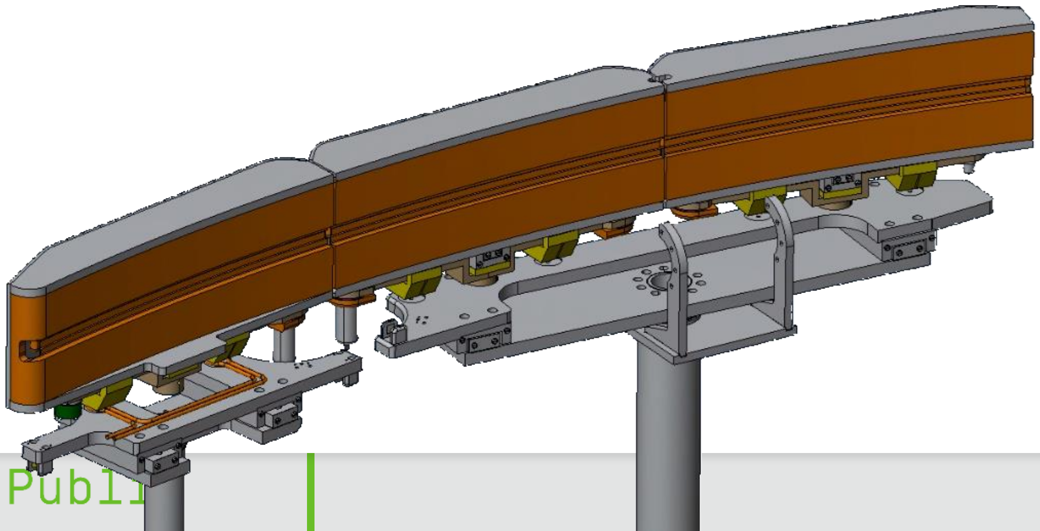
Design phase

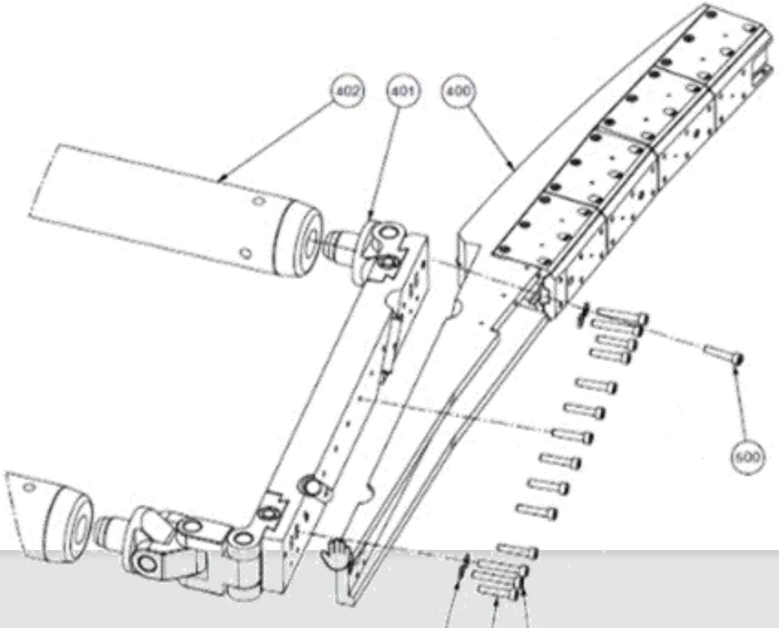
- Entrance position, exit position, gap are adjustable
- Foreseen operating voltage: <50 kV

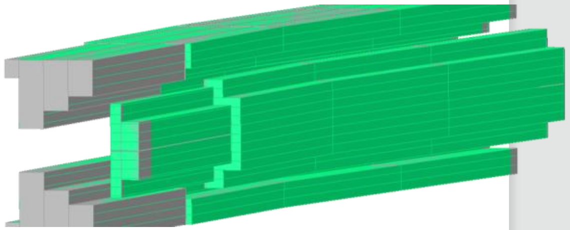
GC

Manufacturing

- Entrance position, exit position are adjustable



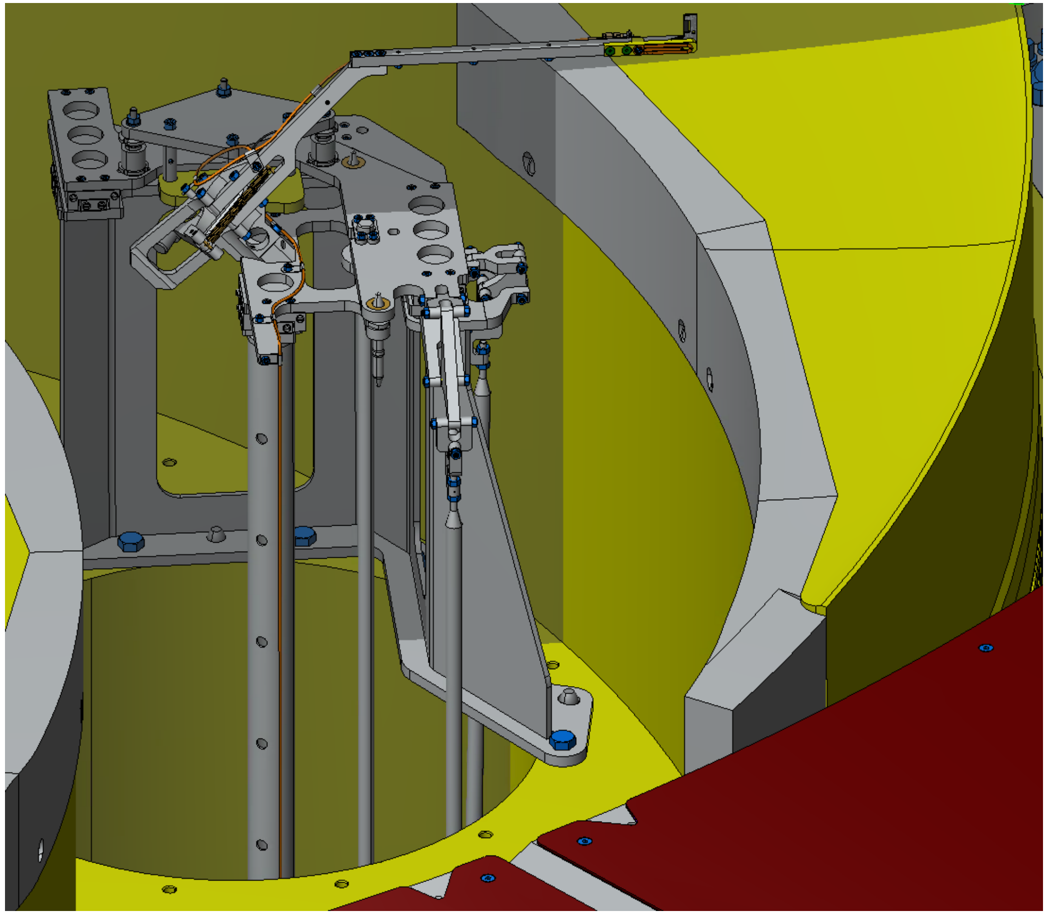




Stripper

Drawings released

- 25 by 100 mm position **adjustability**
- <0.1 mm position **repeatability**
- Stripper **must be removed** from the median plan to accelerate carbon
- Stripper is a **consumable** which needs to be replaced periodically.
  We want to replace it without breaking the cyclo vacuum.
- Stripper **environment**
  - no room to have a radial arm holding the stripper from outside
  - Stripper is between the poles, no simple vertical holding arm



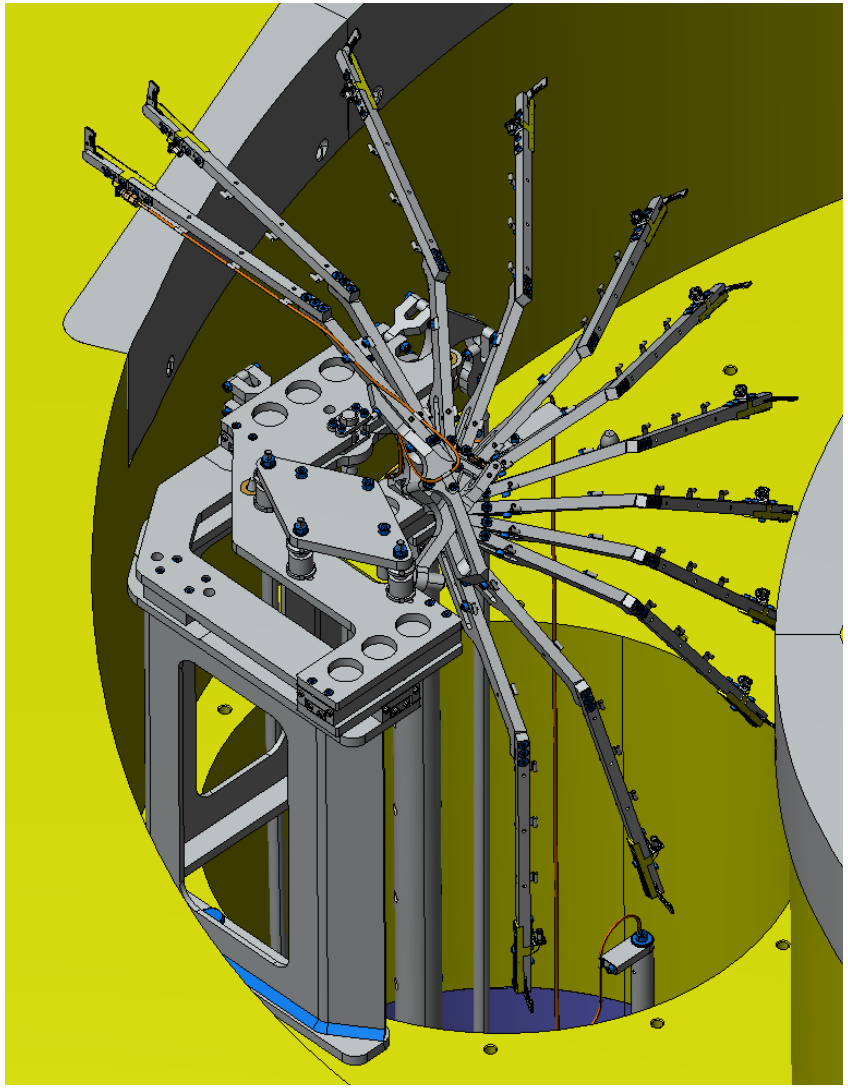
Design updates: Stripper

Drawings released

Stripper motion to air lock:

Combined motions of the holding arm

rotation (horizontal to vertical) + vertical translation



Design updates: Stripper

Drawings released

Sequence In the airlock:

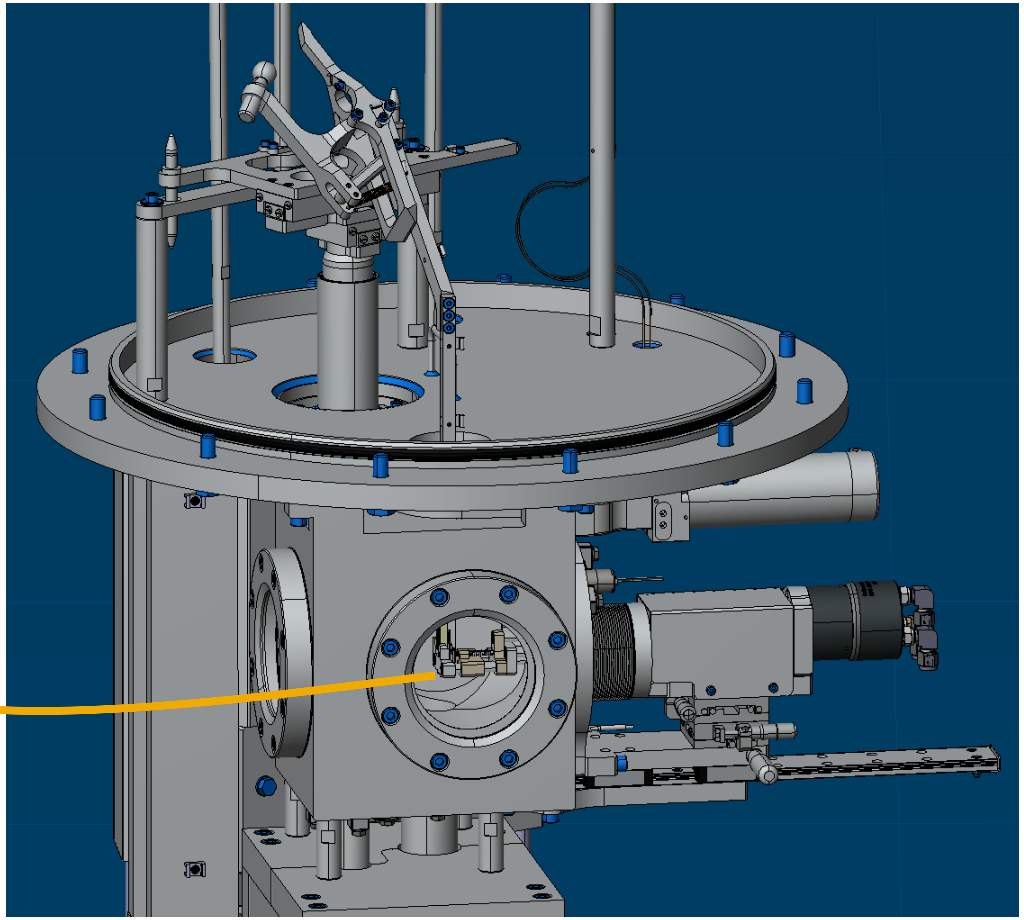
1 – “Fork docking”: Fork locked on a pin

2 – Separation from its holding arm

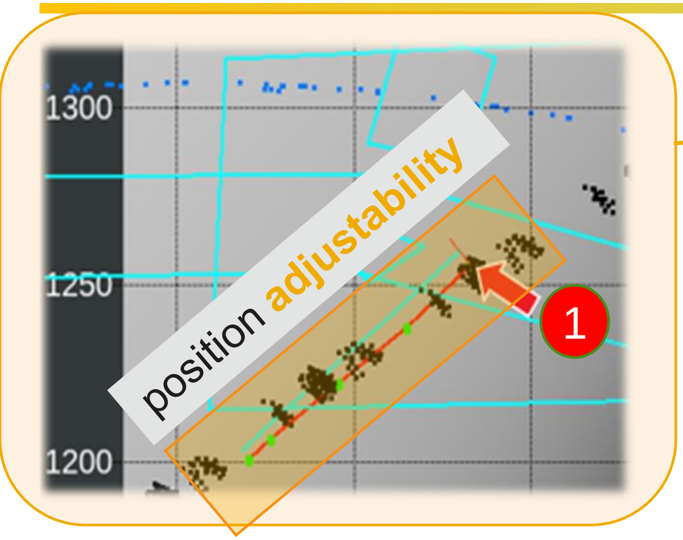
3 – Arm goes back out of the airlock

4 – Closing the gate

5 – Venting

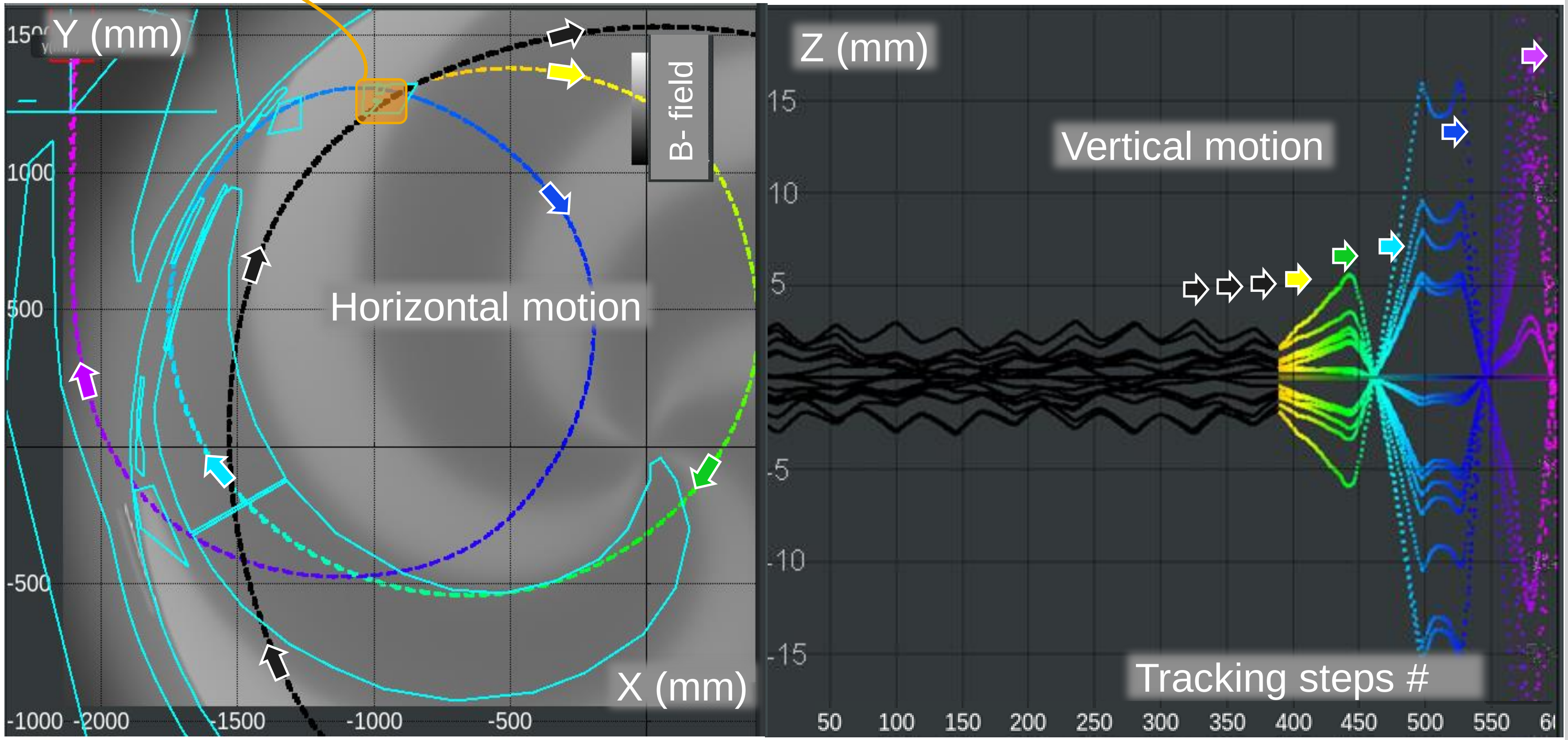


Protons extraction dynamics



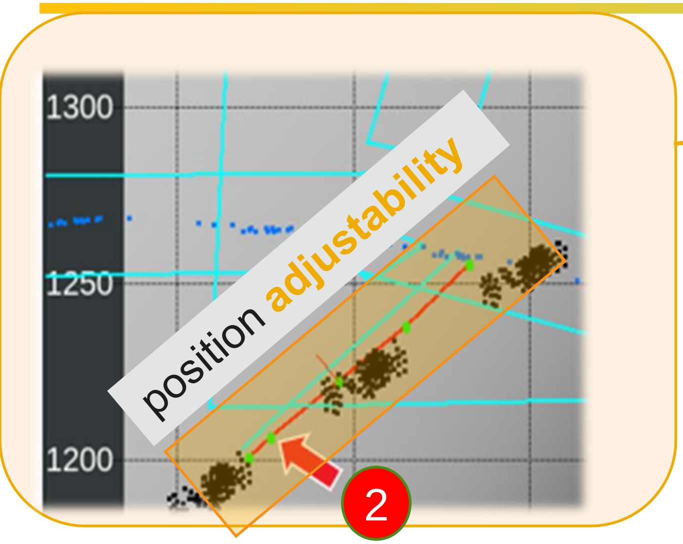
Zoom @ stripper location

Protons extraction: up to cryostat exit flange ; Stripper position 1



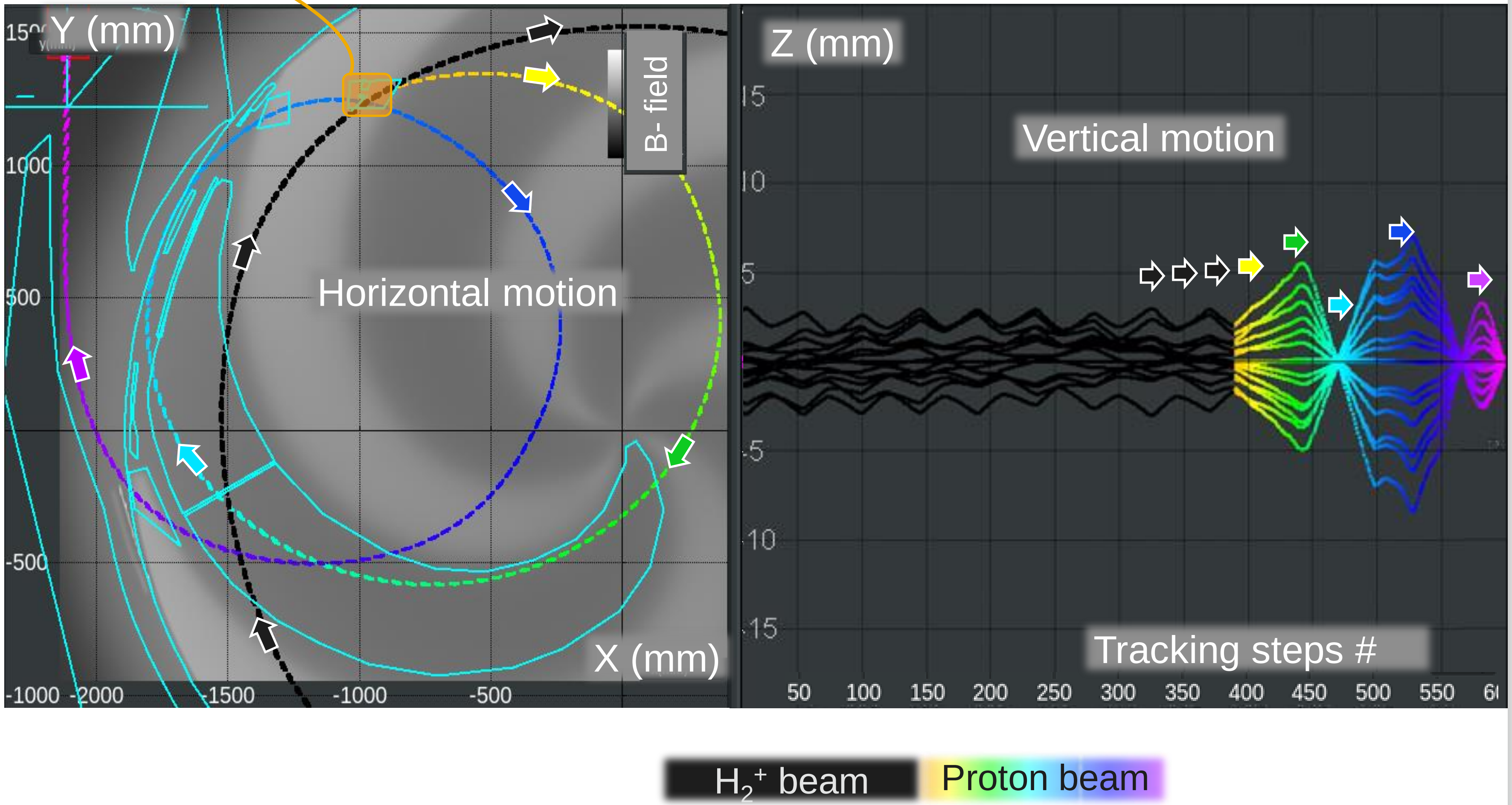
H_2^+ beam Proton beam

Protons extraction dynamics

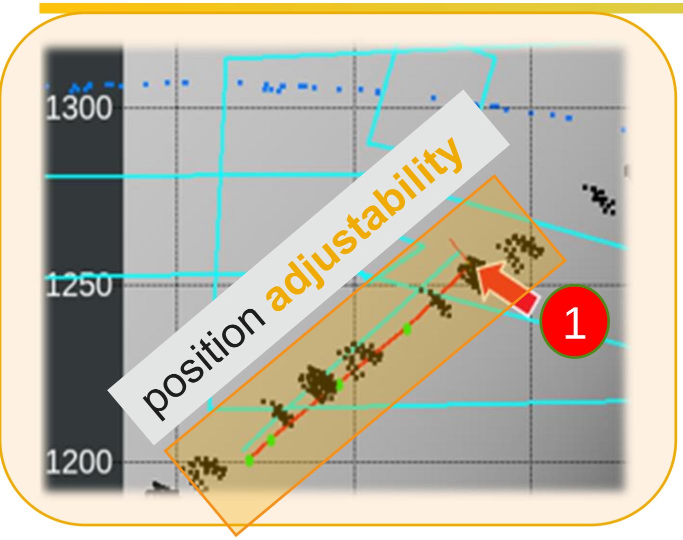


Zoom @ stripper location

Protons extraction: up to cryostat exit flange ; Stripper position 2

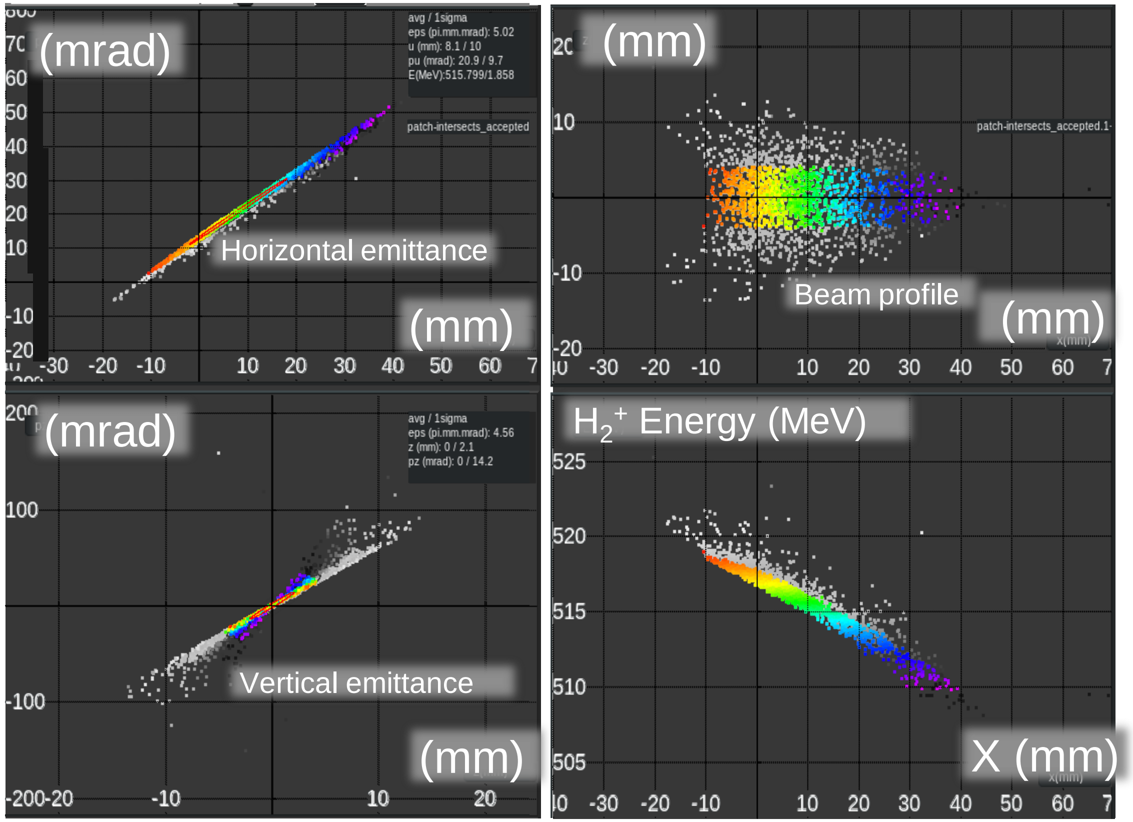


Protons extraction dynamics



@ stripper location

Beam @ cryostat exit flange ; Stripper position 1

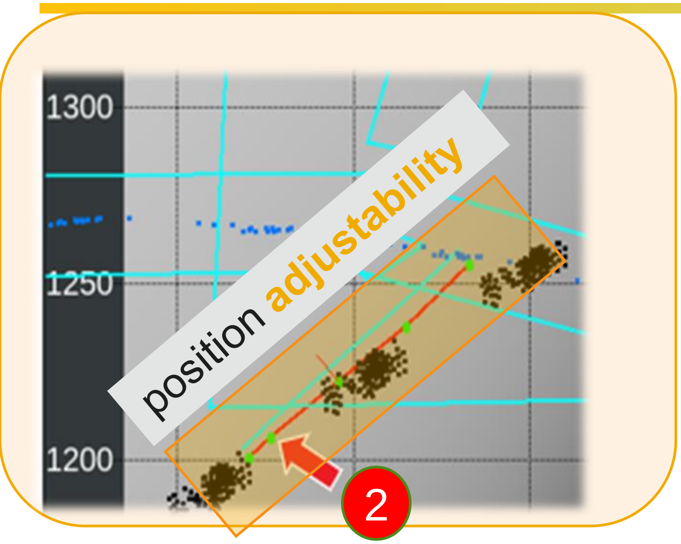


Considering hits on internal geometry:

Acceptance

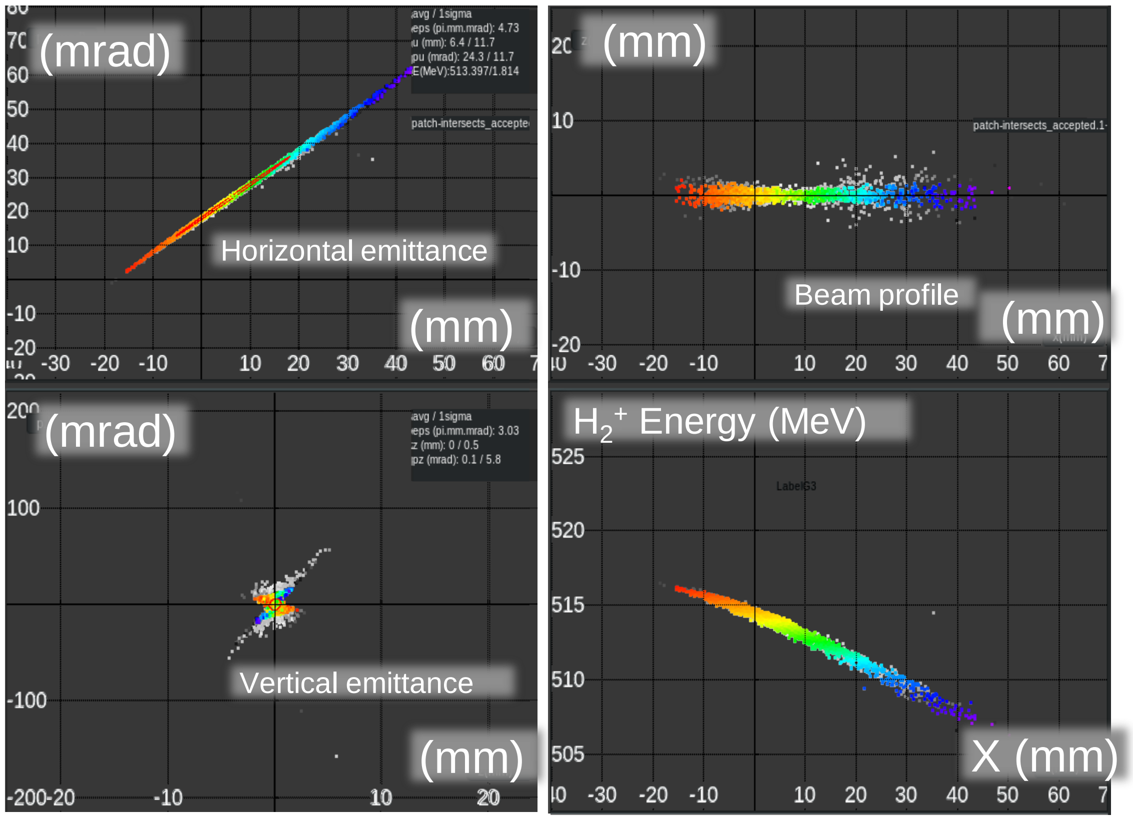
➔ Following beam lines designed for large acceptance

Protons extraction dynamics



@ stripper location

Beam @ cryostat exit flange ; Stripper position 2



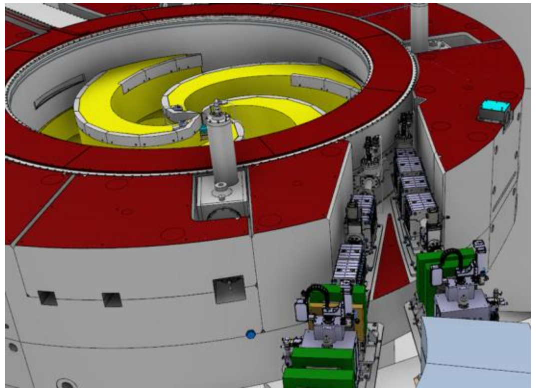
Considering hits on internal geometry:

Acceptance

➔ Following beam lines designed for large acceptance

Extraction tables

Final review



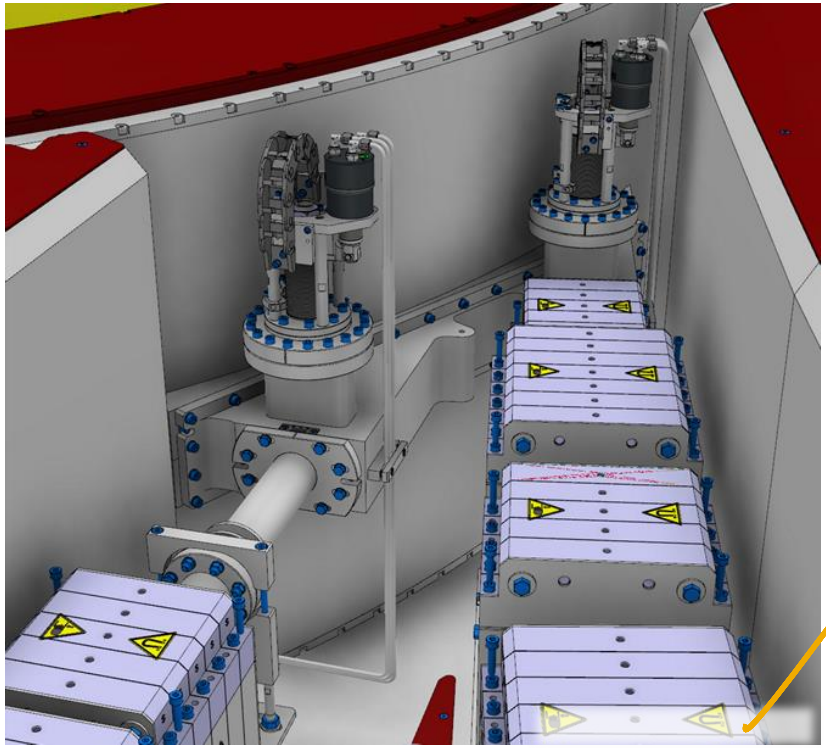
On each extraction line, in yoke flux returns, we found:

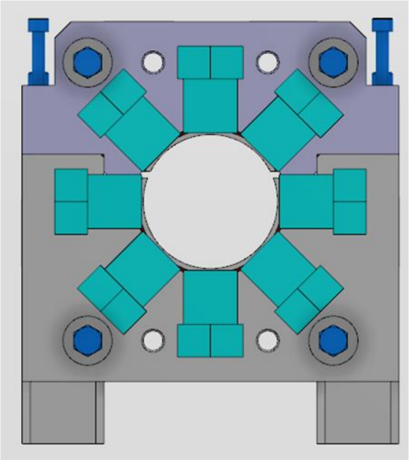
1 – BPMs* on cryostat exit flange

2 – followed by PMQ** sub assemblies

- *Beam Profile Monitor*

*** Permanent magnets quadrupole*





Extraction tables

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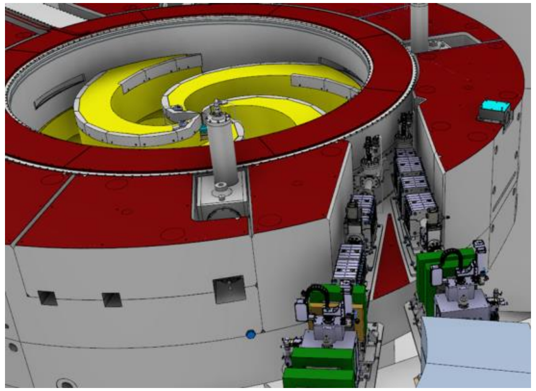

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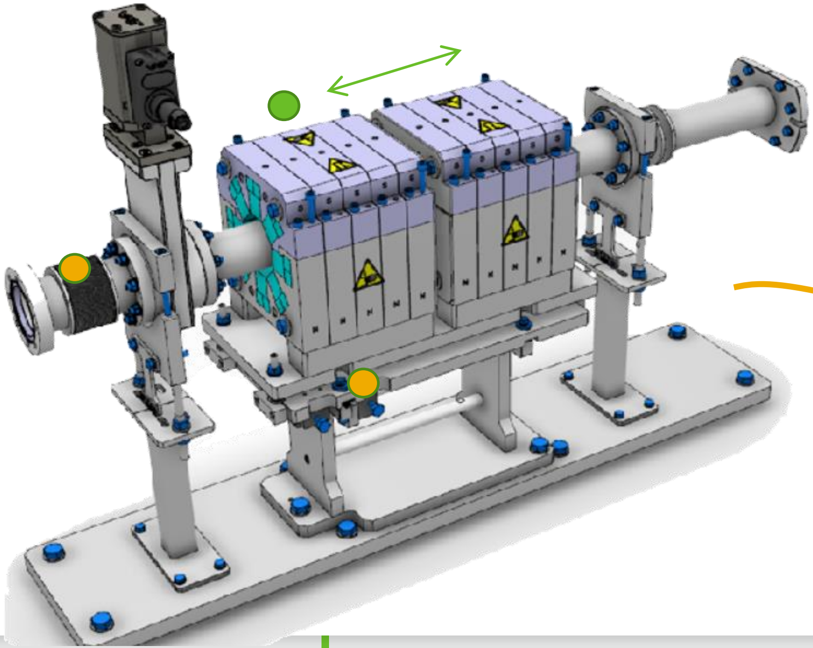
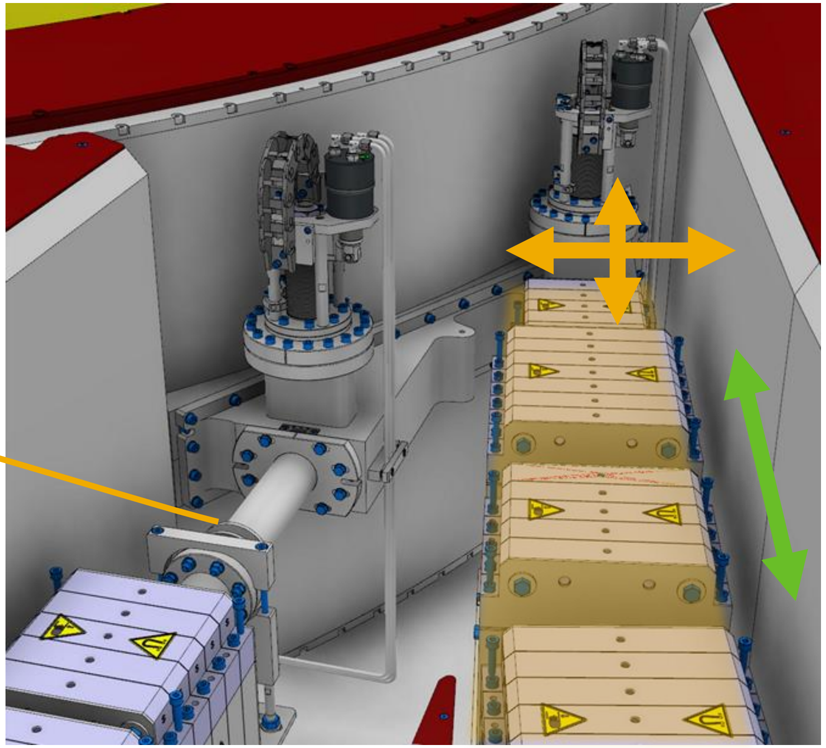
2 – followed by PMQ** sub assemblies

- *Beam Profile Monitor*

*** Permanent magnets quadrupole*





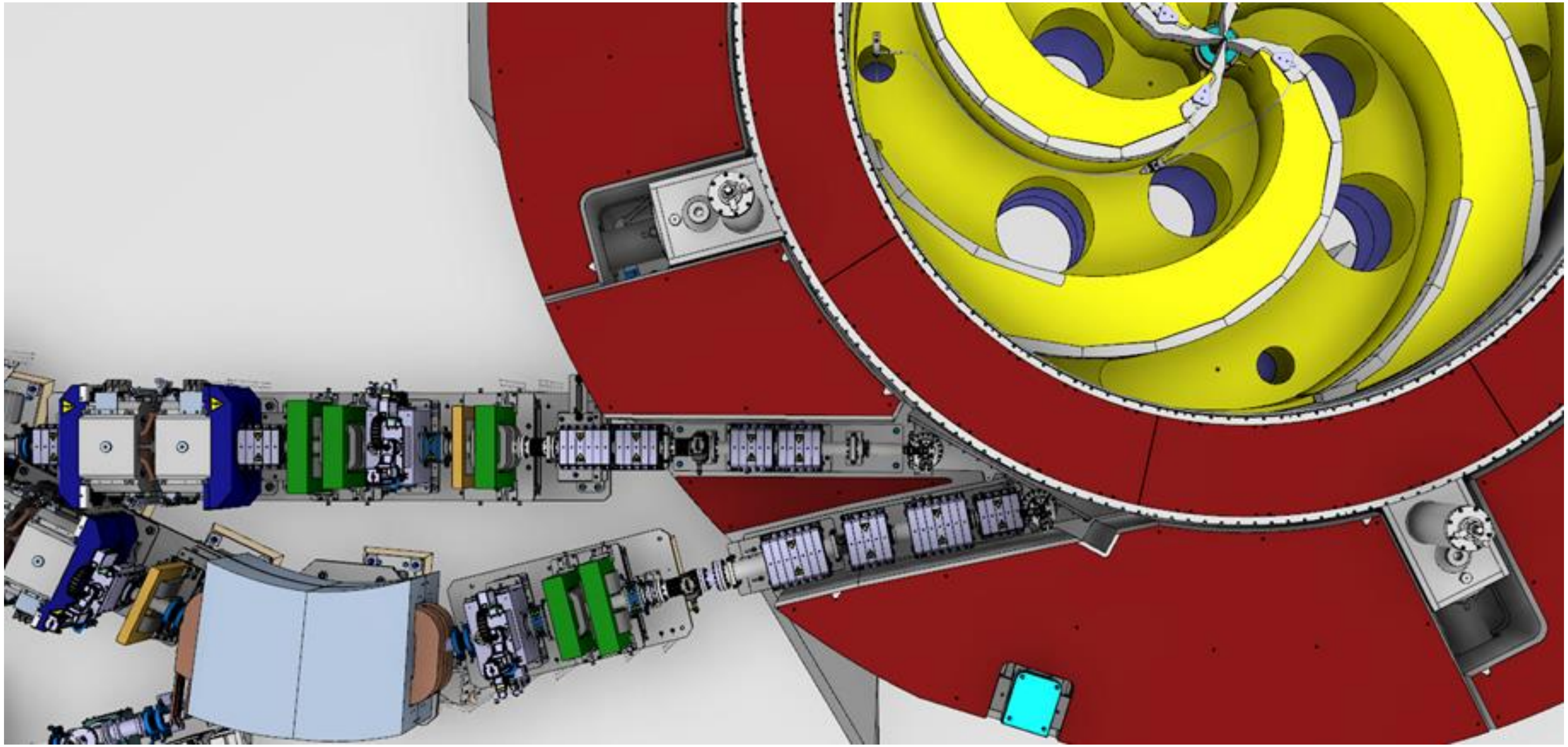
Steering & focusing can be adjusted

Extraction lines

Manufacturing

NHa NORMANDY HADRONTHERAPY

Space constraint…



Fundamental resonance crossing

Minimize beam losses:

- Crossing the resonance FAST ➔ **specific profiles on pole edges crossing.**
- Good centering of the beam ➔ **“phase selection” & harmonic coils in central region.**

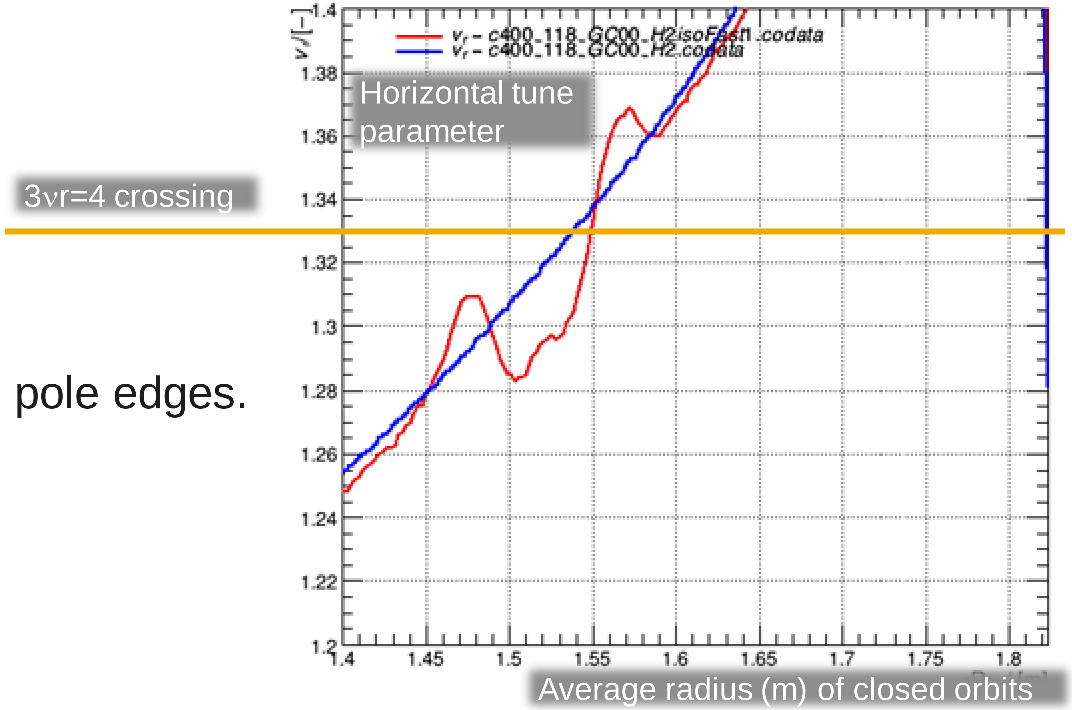
Limit the impact of the residual losses: Use of collimators.

Fundamental resonance crossing

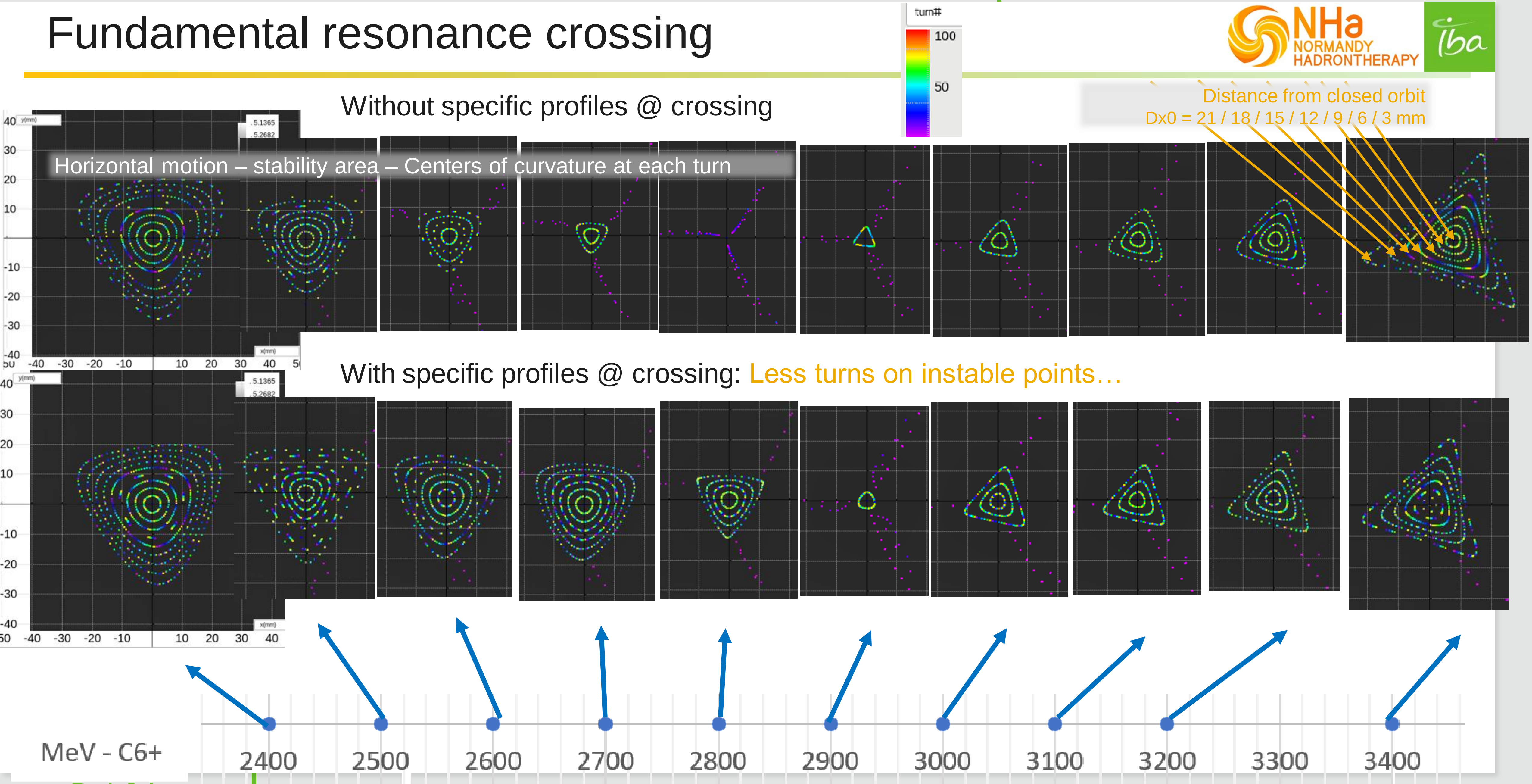
Minimize beam losses:

- Crossing the resonance FAST ➔ **specific profiles on pole edges crossing.**

In practice: A groove and a rod on pole edges.

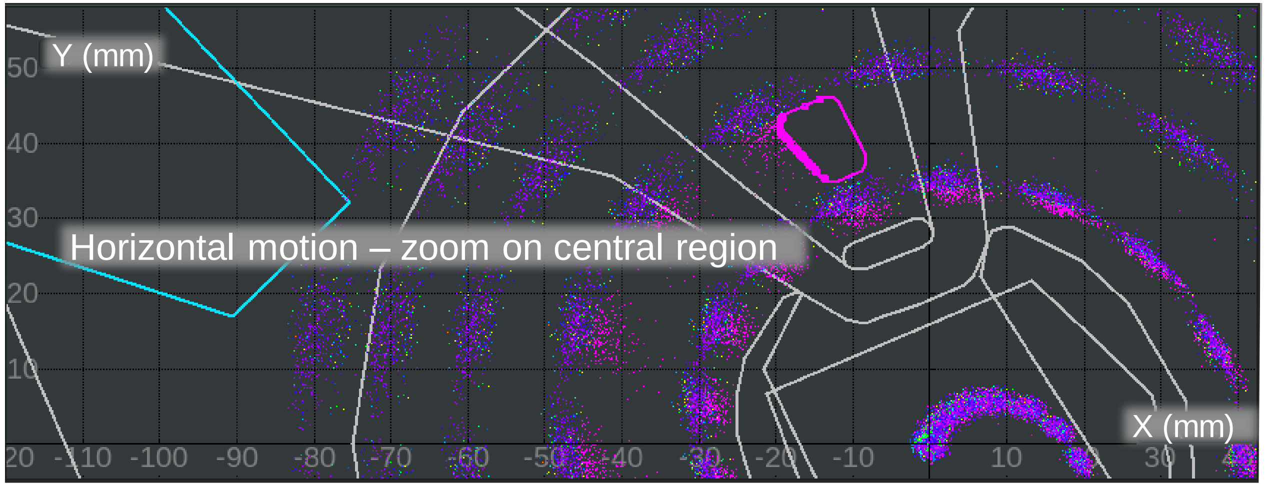


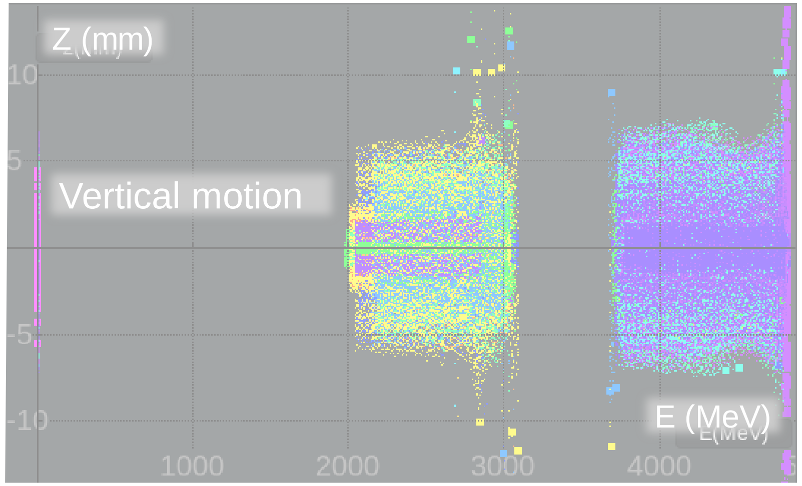
Fundamental resonance crossing



Fundamental resonance crossing

Complete dynamics model: Beam from axial injection to cryostat exit flange

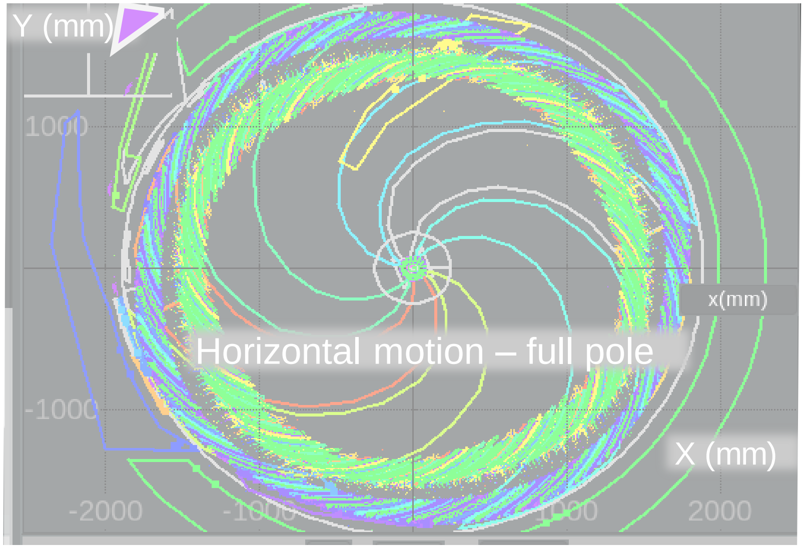


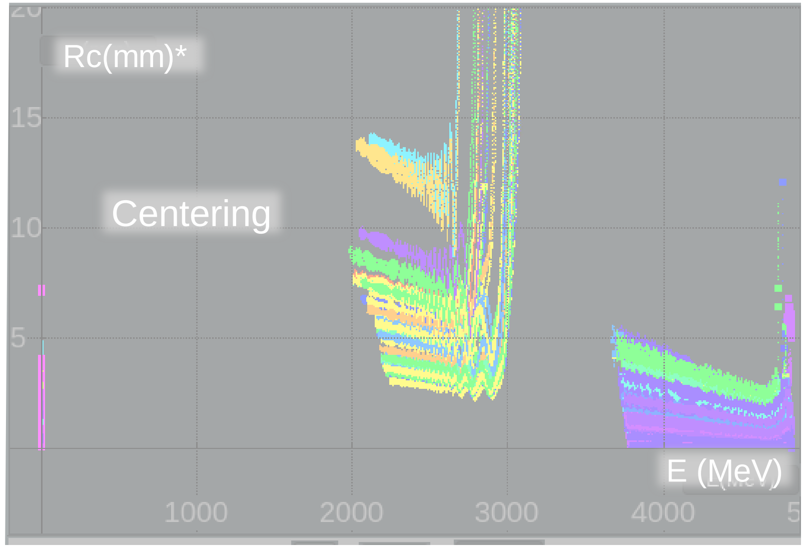


Color is given by element hit 1rst:
Dee#1 ; Dee#2 ; Cryostat ;
***Alum. Collimator** ; …etc.*

In center: ***Phase selector pillar***

Cryostat exit Flange

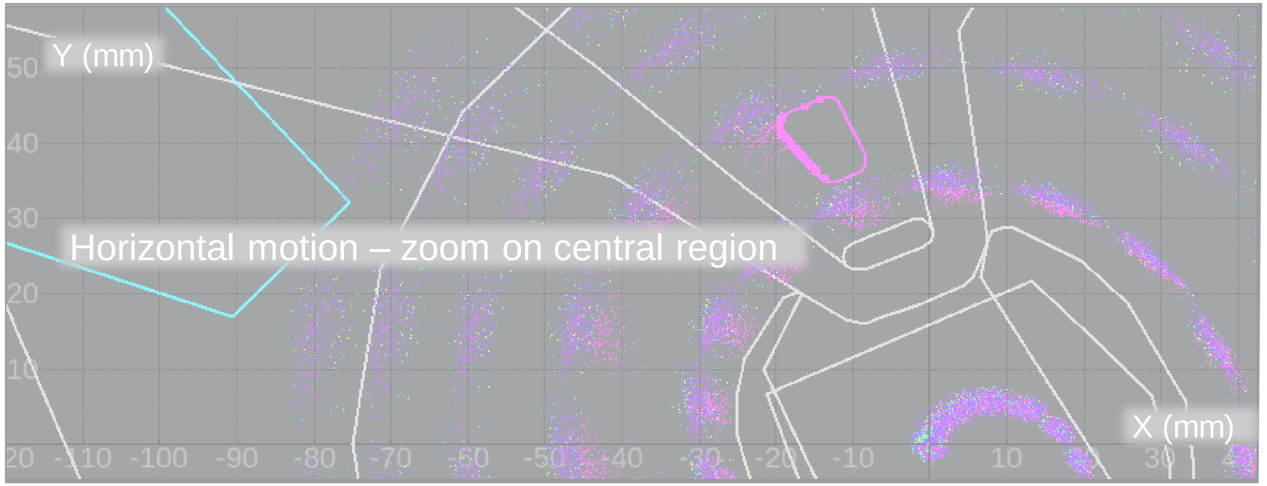


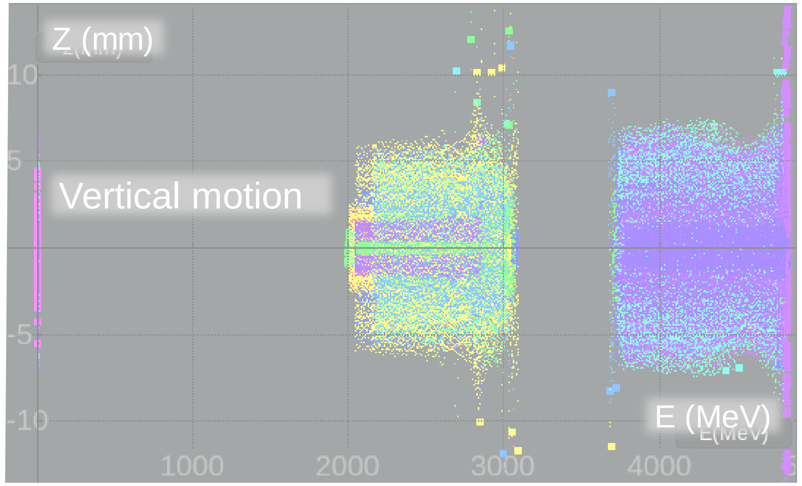


** Radius of (averaged on 1 turn) center of curvature*

Fundamental resonance crossing

Complete dynamics model: Beam from axial injection to cryostat exit flange





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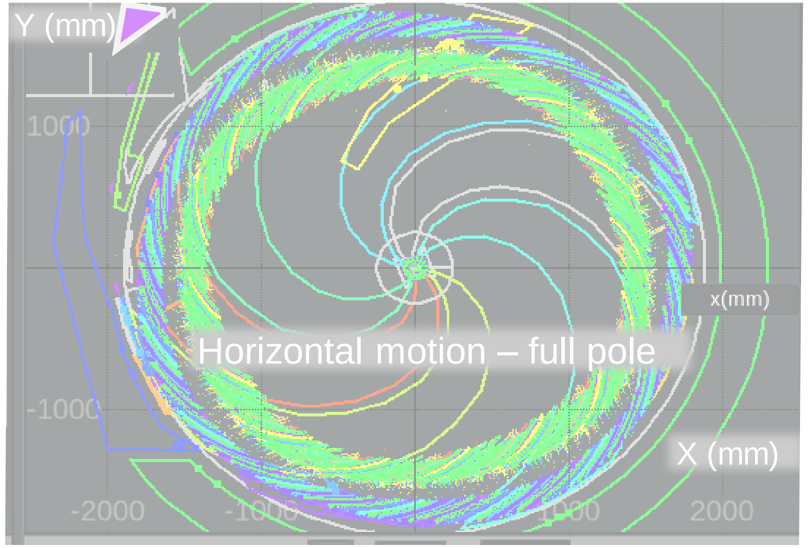
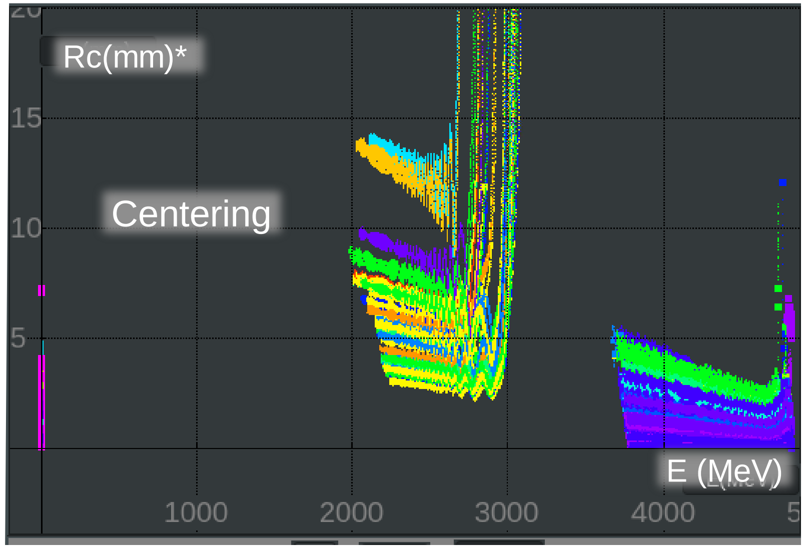
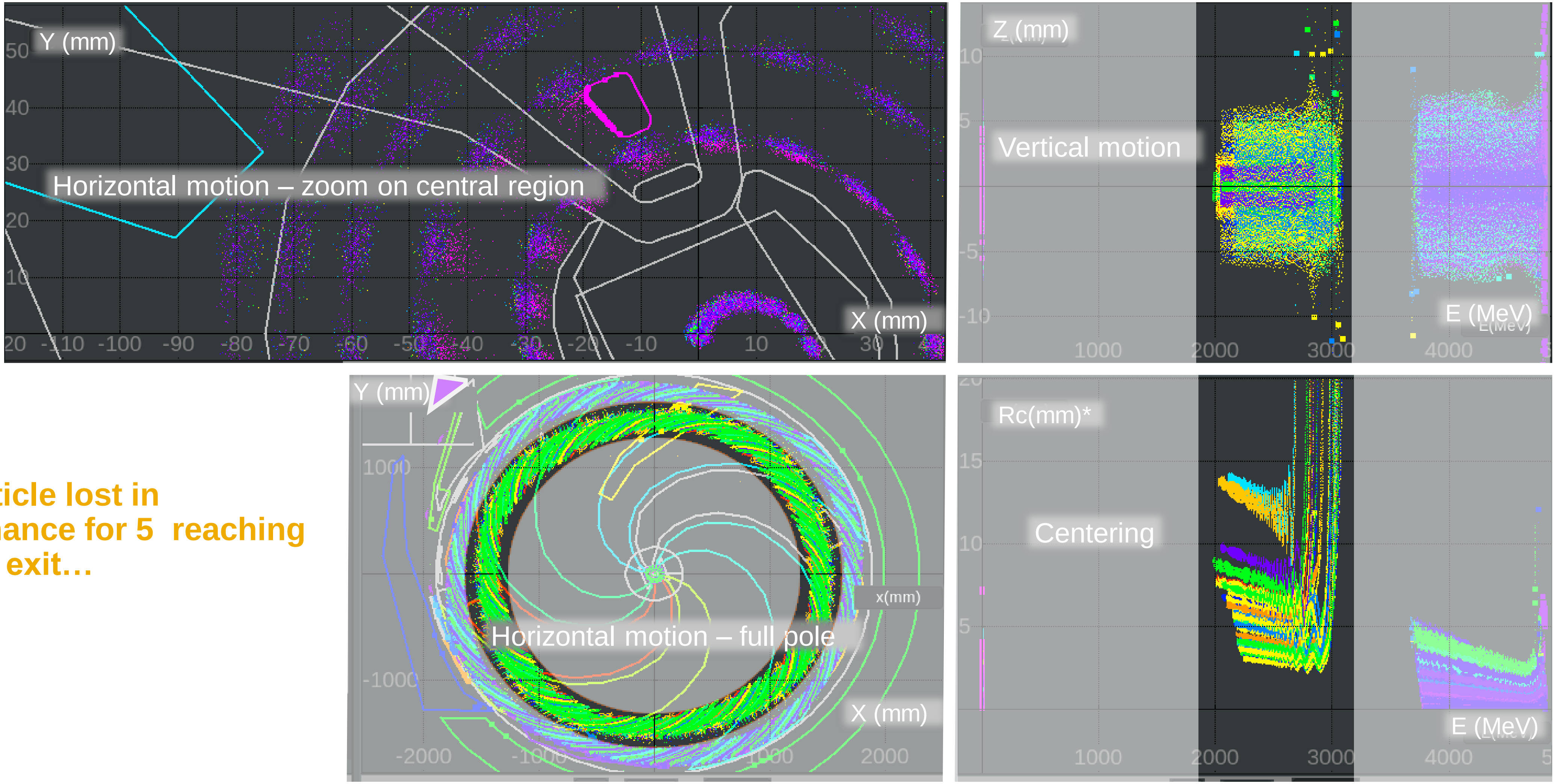




* *Radius of (averaged on 1 turn) center of curvature*

Fundamental resonance crossing

Losses at resonance crossing: off centered particles



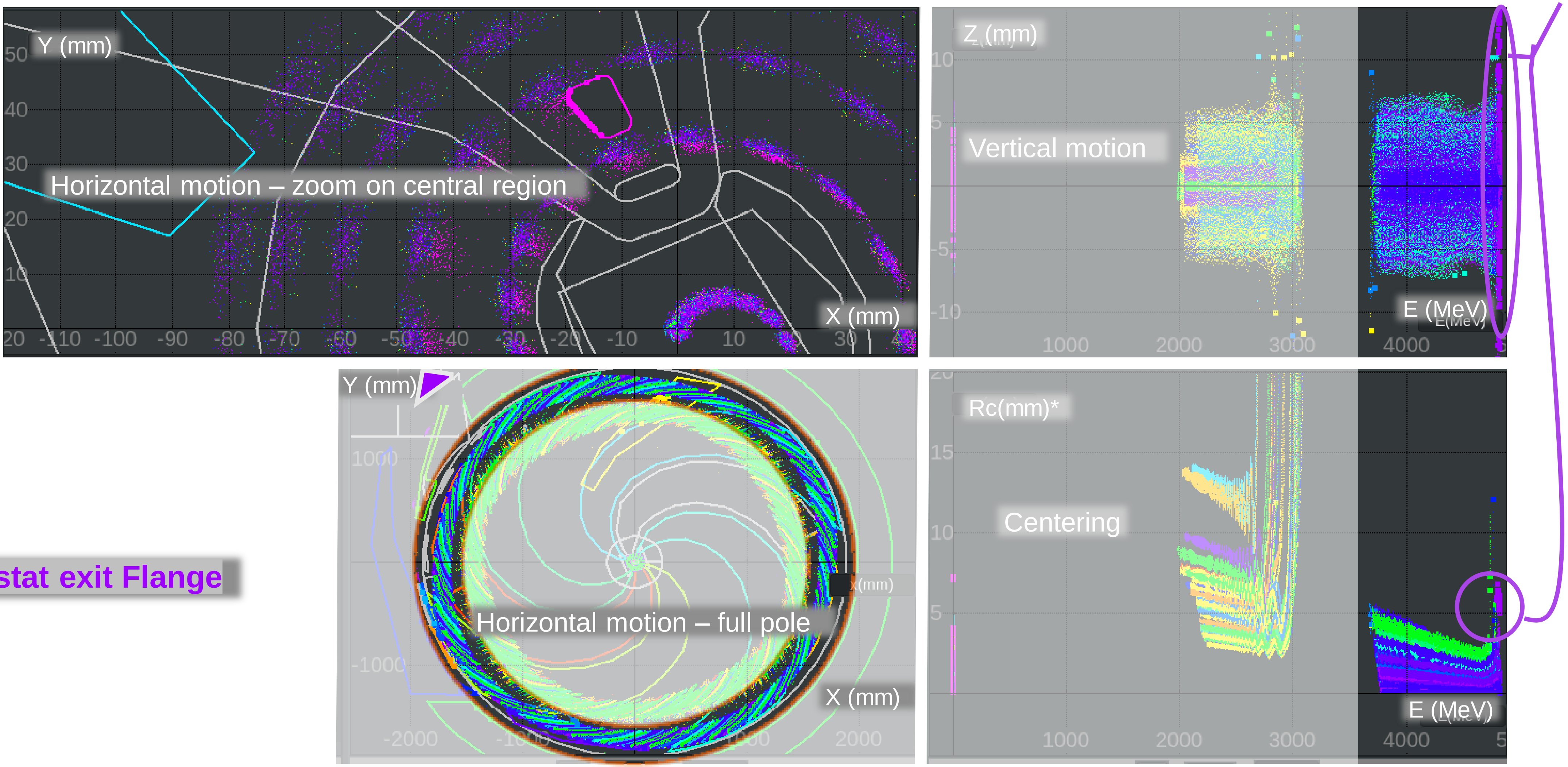
1 particle lost in resonance for 5 reaching cyclo exit…

** Radius of (averaged on 1 turn) center of curvature*

Fundamental resonance crossing

Some particle reaching max energy:

Beam reaching exit flange

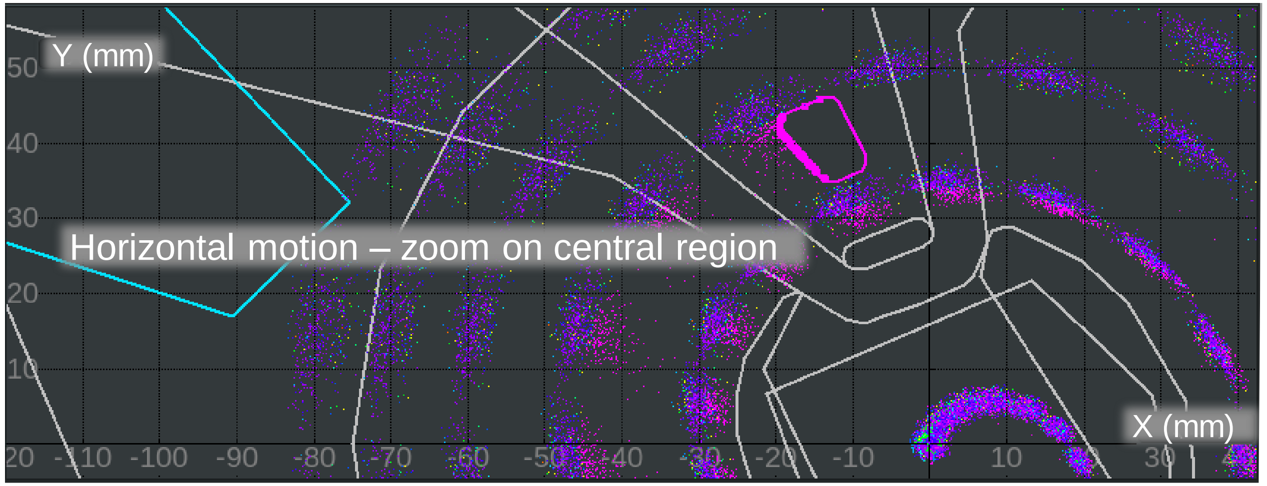


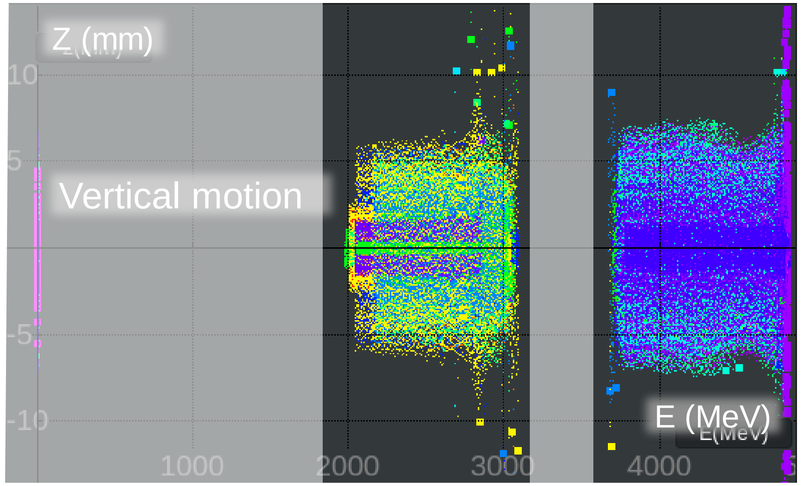
Cryostat exit Flange

* *Radius of (averaged on 1 turn) center of curvature*

All in all

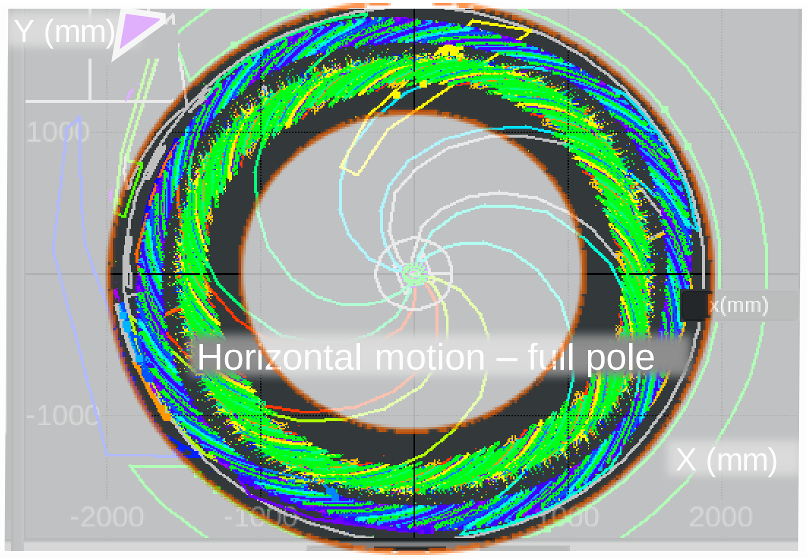
Some lost at resonance crossing: off centered particles

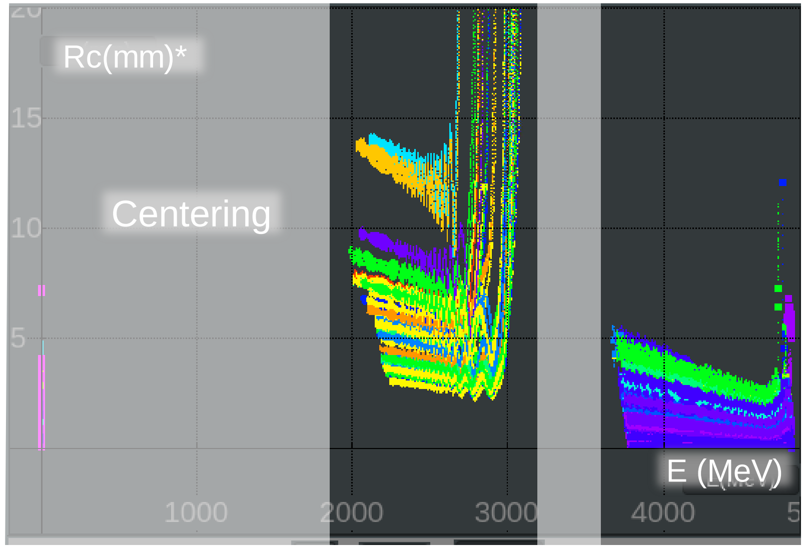




50% of the accelerated beam reach cyclotron exit.

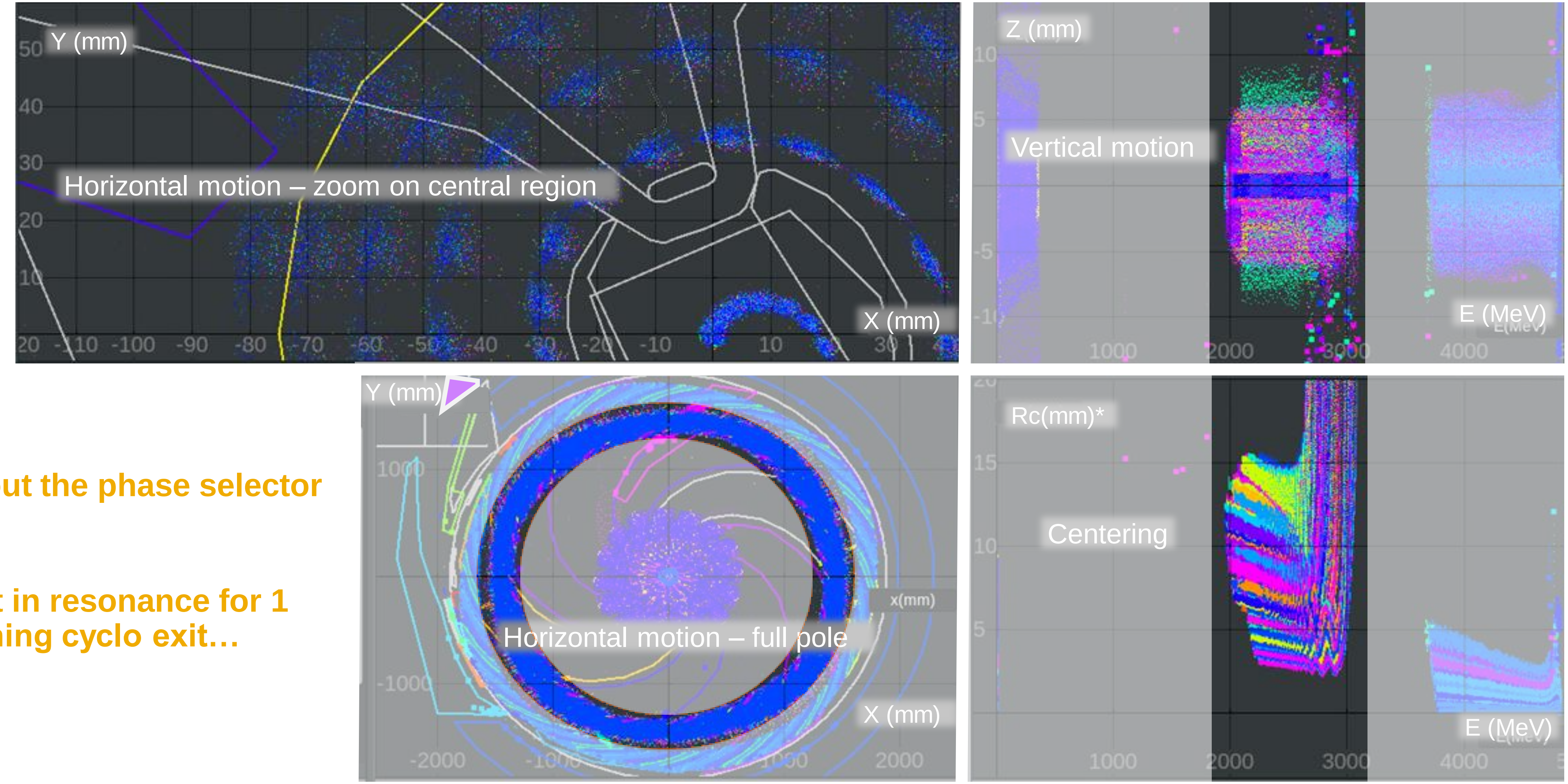
Among losses, 60% touch the deflector.





* *Radius of (averaged on 1 turn) center of curvature*

Fundamental resonance crossing



without the phase selector pillar

1 lost in resonance for 1 reaching cyclo exit…

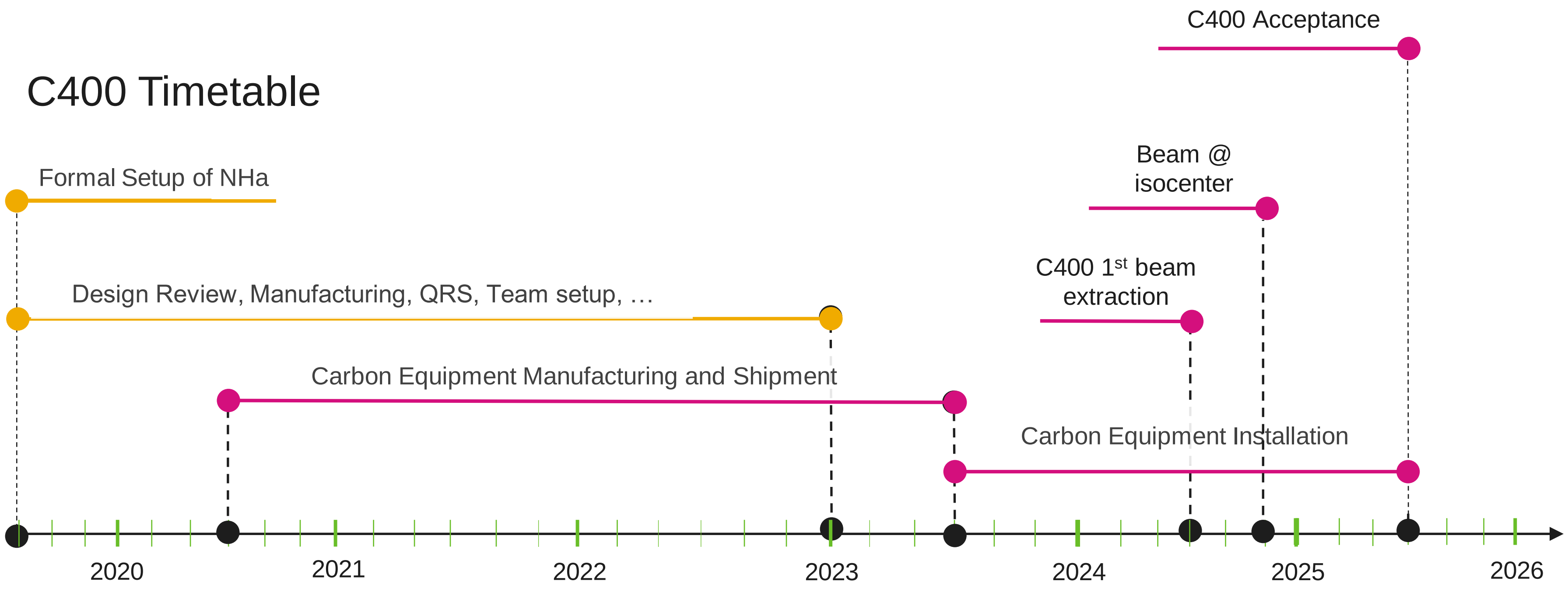
** Radius of (averaged on 1 turn) center of curvature*

Conclusions

Starting from 2009 design, we did a final pass on all subsystems.

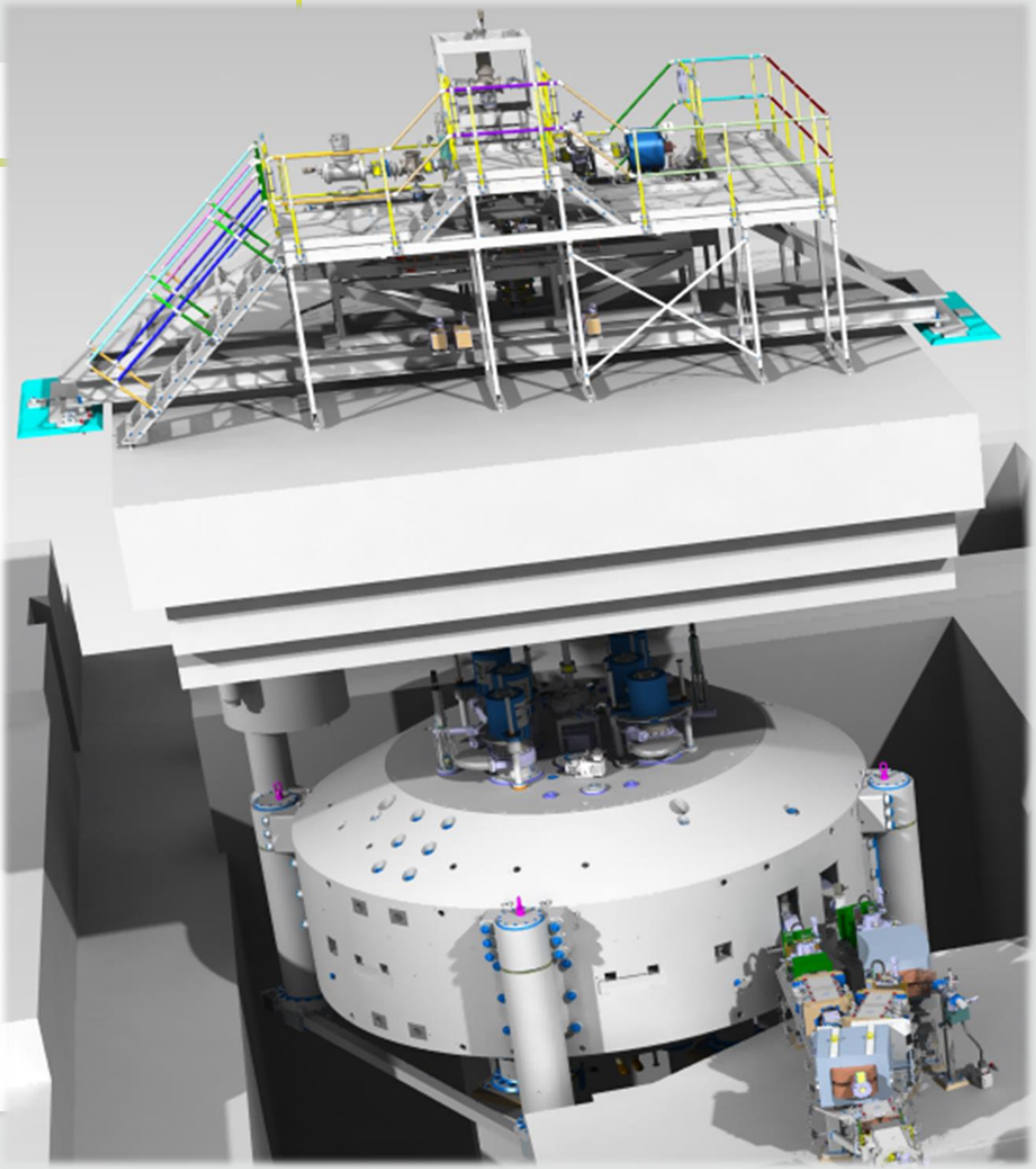
C400 is now under construction.

Any aspect of such a large cyclotron needs detail studies.



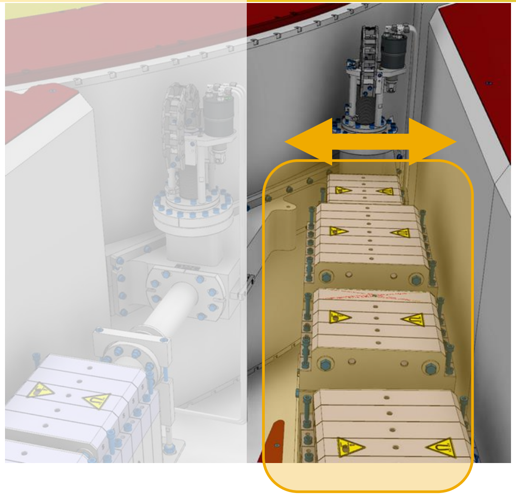
Thank you for your attention

ANY QUESTIONS ?



Extraction tables

Final review



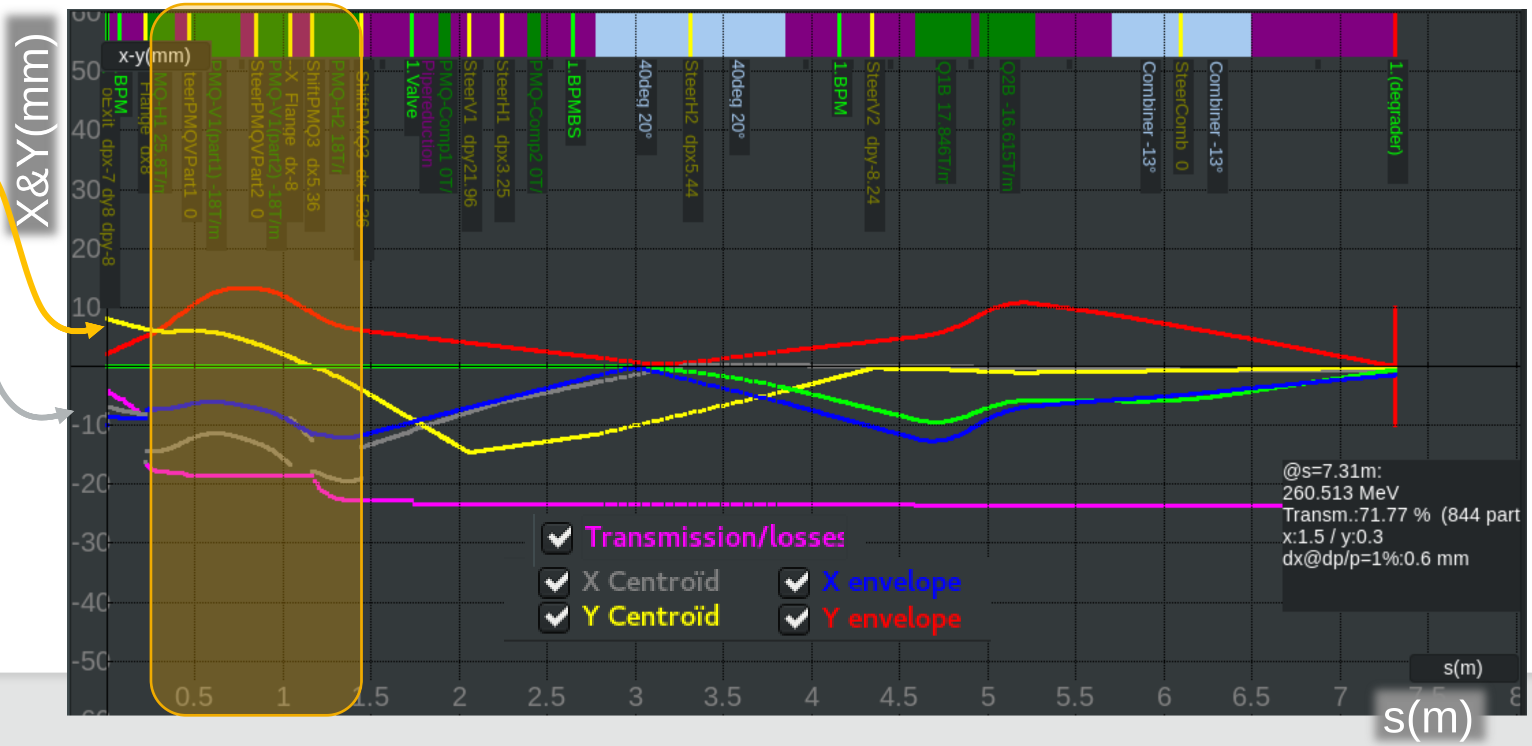
# 4cm-slices	Sm2Co17 Test #1
PMQ-H1	4
PMQ-V1-1	7
PMQ-V1-2	5
PMQ-H2	7

Optics from cyclotron to double waist on range shifter.

Alignment *(position & direction)* error
Vertical & Horizontal

In X (Horiz.)
-8mm / -8mrad

In Y (Vertical)
8mm / -8mrad



Introducing …

Normandy Hadrontherapy (NHa) located in Caen, France

- 2 main shareholders: **IBA** & **SAPHYN** (Normandy Region).
- Several other industrial and institutional partners joined the project

Owning about **40%** of the shares, **IBA** is:

- (i) the largest equity stakeholder
- (ii) industrial shareholder of NHa.

IBA:

- Accelerators technology is in IBA DNA
- Design of the C400 heavy ion cyclotron (Based on IBA design – Transfer of IP)
- All the other element(s) of the treatment rooms (IGPT, workflow and integration) using IBA technology
- Largest equity shareholder of NHa and authorized partner to market the new heavy ion system

NHa Normandy Hadrontherapy:

- Design, produce and market C400 IONS system
- Build a multiple heavy ions particle Radiation Oncology department in Caen with research capacity (Biology and Physics)
- Supported by the Normandy Region (French state) already hosting GANIL to become a leading European center for research and treatment in hadrontherapy

Colombe Investment

Design, produce and market the ion therapy system